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Evaluation of the Riley Stoker Corporation Distributed Mixing Burner

Riley Stoker Corp., Worcester, MA

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EVALUATION OF THE RILEY STOKER CORPORATION DISTRIBUTED MIXING BURNER

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16. ABSTRACT The report gives results of an evaluation of the NOx performance and sulfur capture potential of a Riley Stoker Corporation low-NOx distributed mixing burner. The performance of the full-scale single burner was verified over typical boiler operating ranges of load and excess air. Combustion efficiency was acceptable, and measured NOx emissions were well below New Source Performance Standards. In summary, tests showed that: (1) optimized NOx emissions from the three coals tested ranged from 205 to 245 ppm, corrected to 3% O2; (2) carbon utilization exceeded 98.8% for all coals at optimum conditions; (3) there was no measurable effect of coal composition on the degree of SO2 reduction with any of the sorbent/injection location combinations; (4) injection of hydrated lime through the tertiary air ports provides the most effective SO2 capture, achieving an estimated 45 to 57% at a Ca/S molar ratio of 2; and (5) injection location did not make a significant difference in SO2 reduction with limestone. SO2 capture was about 35% at a Ca/S molar ratio of 2. (The reduction of NOx, SOx, and particulate emissions from utility and industrial boilers has been a high priority concern of the U.S. EPA and all of the major boiler burner manufacturers. As part of EPA's program, the Limestone Injection into a Multistage Burner (LIMB) is aimed at these pollutants.)

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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Burners	Stationary Sources	13A 08G
Coal	Distributed Mixing Burners	21D 07B
Nitrogen Oxides		
Sulfur Oxides		
Combustion		21B
Efficiency		
Limestone		

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ABSTRACT

The reduction of NO_x, SO_x, and particulate emissions from utility and industrial boilers has been a high priority concern of the U.S. EPA and all of the major boiler burner manufacturers. As part of EPA's program, the Limestone Injection into a Multistage Burner (LIMB) represents one portion of an effort to investigate the economic control of these pollutants.

This report evaluates the NO_x performance and sulfur capture potential of a Riley Stoker Corporation low-NO_x distributed mixing burner.

The performance of a full-scale single burner was verified over typical boiler operating ranges of load and excess air. Combustion efficiency was acceptable and measured NO_x emissions were well below New Source Performance Standard levels. In summary, the burner exhibited: a) optimized NO_x emissions from the three coals tested ranged from 205 to 245 ppm corrected to 3 percent O_2; b) carbon utilization exceeded 98.8 percent for all coals at optimum conditions; c) there was no measurable effect of coal composition on the degree of SO_2 reduction with any of the sorbent/injection location combinations; d) injection of hydrated lime through the tertiary air ports provides the most effective SO_2 capture, achieving an estimated 45 to 57 percent at a Ca/S molar ratio of two; and e) injection location did not make a significant difference in SO_2 reduction with limestone. SO_2 capture was approximately 35 percent at a Ca/S molar ratio of two.

TABLE OF CONTENTS

Section		Page
1.0	INTRODUCTION	1
2.0	EXPERIMENTAL SYSTEM	2
	2.1 Riley Stoker Corporation DMB Design	2
	2.2 Coal Spreader Design	2
	2.3 Fuels and Sorbents	5
	2.4 Test Facilities and Procedures	5
3.0	NO_x AND PERFORMANCE OPTIMIZATION OF THE RILEY STOKER Corporation DMB	9
	3.1 Initial Performance Optimization With Utah Coal	15
	3.2 Additional Developmental Optimization for Indiana and Illinois Coals	15
4.0	Sulfur Dioxide Reduction Potential With Sorbent Injection	26
	4.1 Sorbent Injection With Utah Coal	34
	4.2 Sorbent Injection With High-Sulfur Fuels	34
	4.3 Aerodynamics of Sorbent Injection	39
5.0	CHARACTERIZATION OF THE RILEY STOKER CORPORATION DMB	42
	5.1 Internal Flame Temperature Profile	49
	5.2 Fly Ash Characteristics	49
	5.2.1 Particle Mass Loading	52
	5.2.2 Particle Size Distribution	52
	5.2.3 Laboratory Analysis of Ash Composition	54
	5.3 Slagging and Fouling Characteristics	54
	5.4 Concentration of SO_x Species	58
6.0	SUMMARY OF RILEY STOKER CORPORATION DMB PERFORMANCE	64
	6.1 Optimization of Combustion Performance	67
	6.2 SO_2 Reduction Potential	67
	6.3 Summary of Riley Stoker DMB Results	68
NOMENCLATURE		70
REFERENCES		71
APPENDIX A		73
A.0	QUALITY ASSURANCE	74
		78

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TABLE OF CONTENTS (Concluded)

Section		Page
A.1	Standard Measurements	78
A.1.1	Air Distribution	78
A.1.2	Air Preheat and Combustor Wall Temperatures	78
A.1.3	Gas Phase Species	78
A.1.4	Pretest Oil Check	80
A.1.5	Particulate Samples (Grab Sample)	83
A.1.6	Fuel Size Distribution	84
A.1.7	Valid Data Acquisition	84
A.1.8	Fuel Flow Rate	87
A.2	Detailed Measurements	87
A.2.1	Instrument Performance Test	87
A.2.2	Sorbent Feed Rate Calibration	89

LIST OF FIGURES

Figure		Page
2-1	The Riley Stoker Corporation 100 x 10^6 Btu/hr Distributed Mixing Burner	3
2-2	Spreader #1--Controlled Combustion Venturi spreader for Riley Stoker Corporation Distributed Mixing Burner	6
2-3	Impeller designs based on 4-in. support tube for Riley Stoker Corporation Distributed Mixing Burner	6
2-4	Large watertube boiler simulator system schematic	11
3-1	Riley Stoker Corporation DMB unstaged performance with CCV spreader	16
3-2	Effect of register position on unstaged performance with Spreader #2 and 12" tertiary ports	18
3-3	Staged performance with Spreader #2 and 12-in. tertiary ports	19
3-4	Effect of tertiary velocity on Riley Stoker Corporation DMB staged performance with Spreader #2	21
3-5	Effect of secondary air distribution on staged performance with Spreader #2 and 8-in. tertiary ports	22
3-6	Staged performance with Spreader #2 and 8" tertiary ports	24
3-7	Effect of excess air on staged performance with Spreader #2 and 8-in. tertiary ports	25
3-8	Effect of Spreader #2 and nozzle position on Riley Stoker Corporation DMB performance with Indiana coal	27
3-9	Summary of Riley Stoker Corporation DMB performance	30
3-10	Effect of excess Air on Riley Stoker Corporation Distributed Mixing Burner emissions	31
3-11	Effect of load on Riley Stoker Corporation Distributed Mixing Burner emissions with optimized spreader	33
4-1	Summary of sorbent injection with Utah coal	36
4-2	Effect of burner parameters on SO_2 capture with Vicron injected through tertiary air ports	37
4-3	Effect of load on SO_2 capture with Utah coal	40

LIST OF FIGURES (Concluded)

Figure		Page
4-4	Summary of sorbent injection with Indiana coal	41
4-5	Summary of sorbent injection with Illinois coal	43
4-6	Effect of coal composition on SO_2 capture	44
4-7	Effect of injection velocity on SO_2 capture with Vicron	46
5-1	In-flame temperature profile of horizontal plane through Riley Stoker Corporation centerline (all temperatures in ^{o}F)	50
5-2	Estimated isotherm contour profile of horizontal plane through Riley Stoker Distributed Mixing Burner centerline . . .	51
5-3	Particle size distributions for Utah coal	55
5-4	Particle size distributions for Indiana coal	56
5-5	Particle size distributions for Illinois coal	57
5-6	Typical thermal history of rear wall slagging panel	61
A-1	The Large Watertube Simulator furnace (LWS) sample train	79

LIST OF TABLES

Table		Page
2-1	Summary of Coal Composition	7
2-2	Summary of Coal Fineness	8
2-3	Sorbent Characteristics	10
2-4	LWS Furnace Characteristics	12
2-5	Standard Measurement Format	13
2-6	Detailed Measurement Format	14
3-1	Summary of the Effect of Nozzle Position on Riley Stoker Corporation DMB performance with Spreader #2 at 6-in. and 8-in. Tertiary Ports	23
3-2	Iterative Development of Riley Stoker Corporation Coal Spreaders for Indiana Coal Firing	28
4-1	Burner Performance During Perturbations for SO_2 Optimization	38
4-2	Sorbent Velocity Ratios Used in Riley Stoker Corporation Sorbent injection tests	47
5-1	Summary of Physical and Chemical Properties of Selected Fly Ash Samples	53
5-2	Comparison of Sorbent Utilization Efficiencies	59
5-3	Indices of Slagging and Fouling Potential for Selected Test Conditions	63
5-4	Measured Levels of SO_x Species With and Without Sorbent Injection	65
6-1	Summary of Riley Stoker Corporation DMB Performance	69
A-1	Program Objectives for Measurement Precision, Accuracy, and Completeness	75
A-2	Sampling Procedures	77
A-3	SO_2 Sample System Daily Log for 7/26/83 (^oF)	81
A-4	Continuous Gas Analyzers	82

LIST OF TABLES (Continued)

Table		Page
A-5	Summary of ASTM Sieve Calibration	86
A-6	Instrument Performance Tests Summary	88

1.0 INTRODUCTION

The initial phase of testing to evaluate Riley Stoker Corporation (RSC) second-generation Low-NO_x burner performance and sulfur capture potential has been completed. This first series of tests involved the optimization of a prototype 100 x 10^6 Btu/hr RSC Distributed Mixing Burner (DMB) followed by the injection of dry sorbent materials for SO_2 reduction. The second phase, to be conducted in the spring of 1984, involves the evaluation of the performance of the RSC Flare burner and the RSC Controlled Combustion Venturi (CCV) burner. The Flare and CCV burners will be tested at two scales, 50 x 10^6 and 100 x 10^6 Btu/hr. Since there is commercial field data available for these latter two burners, the results of the tests from the second phase will establish a data base to relate burner performance in the EPA Large Watertube Simulator (LWS) at Energy and Environmental Research Corporation's (EER) test site with burner performance in field operating boilers. Thus, the second-phase test results will provide data necessary to extrapolate the performance of the RSC DMB from this first series to field boilers.

The burner adjustments and coal spreader design were first optimized for NO_x emissions. The RSC DMB was observed to be sensitive to burner adjustments in terms of stability, flame characteristics, and emissions. It was necessary to make modifications in the coal spreader design and burner adjustments to fire the three different test coals. Following NO_x optimization of the burner parameters, the DMB performance was verified over operating ranges typical of field installations. The SO_2 reduction potential of the RSC DMB was studied using two sorbent types and two injection locations. Perturbations in burner adjustments from the optimum NO_x settings were made during injection of sorbent to determine the optimum burner conditions for SO_2 reduction and the extent of NO_x/SO_x reduction tradeoffs.

This interim report summarizes the results of the first phase of tests that evaluated RSC DMB NO_x/SO_x performance. The optimization of burner parameters, injection of sorbent for SO_x control, and detailed characterizations of the DMB performance are described. Results from quality assurance procedures are included as an appendix.

2.0 EXPERIMENTAL SYSTEM

2.1 Riley Stoker Corporation DMB Design

The RSC DMB was based on EPA DMB design criteria. The design of the burner is shown in Figure 2-1. The following RSC burner components were incorporated into the design.

- Retractable Coal Spreader
- Telescoping Venturi Coal Nozzle
- Dual Parallel Registers for Swirl Control
- Divided Windbox to Separate Inner and Outer Secondary Air
- Tertiary Ports With Removable Inserts
- Peabody Gas Ignition System
- Commercial 2-Color Flame Scanner

The coal and primary air enter the burner through a coal-head which is connected to an axial coal nozzle. The coal-head is equipped with adjustable vanes to produce a uniform coal distribution in the nozzle. The telescoping nozzle adjusts the primary setback within the burner throat. The venturi-shaped nozzle accelerates the coal stream through the throat of the venturi, tending to concentrate the coal particles in the center of the coal pipe prior to reaching the coal spreader. An impeller-type spreader, located at the end of the nozzle, imparts swirl to the coal and primary air, providing for mixing with the secondary air. There are two concentric secondary air passages supplied from individual windboxes. Each air passage is equipped with an adjustable register for swirl control. The separate windboxes, which were incorporated as an experimental expedient, facilitate remote control of the air-flows from the furnace control room. Tertiary or staging air is supplied from four separate ports evenly spaced around the burner exit. Tertiary inserts (8, 10, and 12 inches in diameter) permit evaluation of a range of tertiary velocities. A retractable gas ignition system, including spark ignition, is located 16 inches radially from the burner centerline at 60°. The two-color flame scanner is located 16 inches below the burner

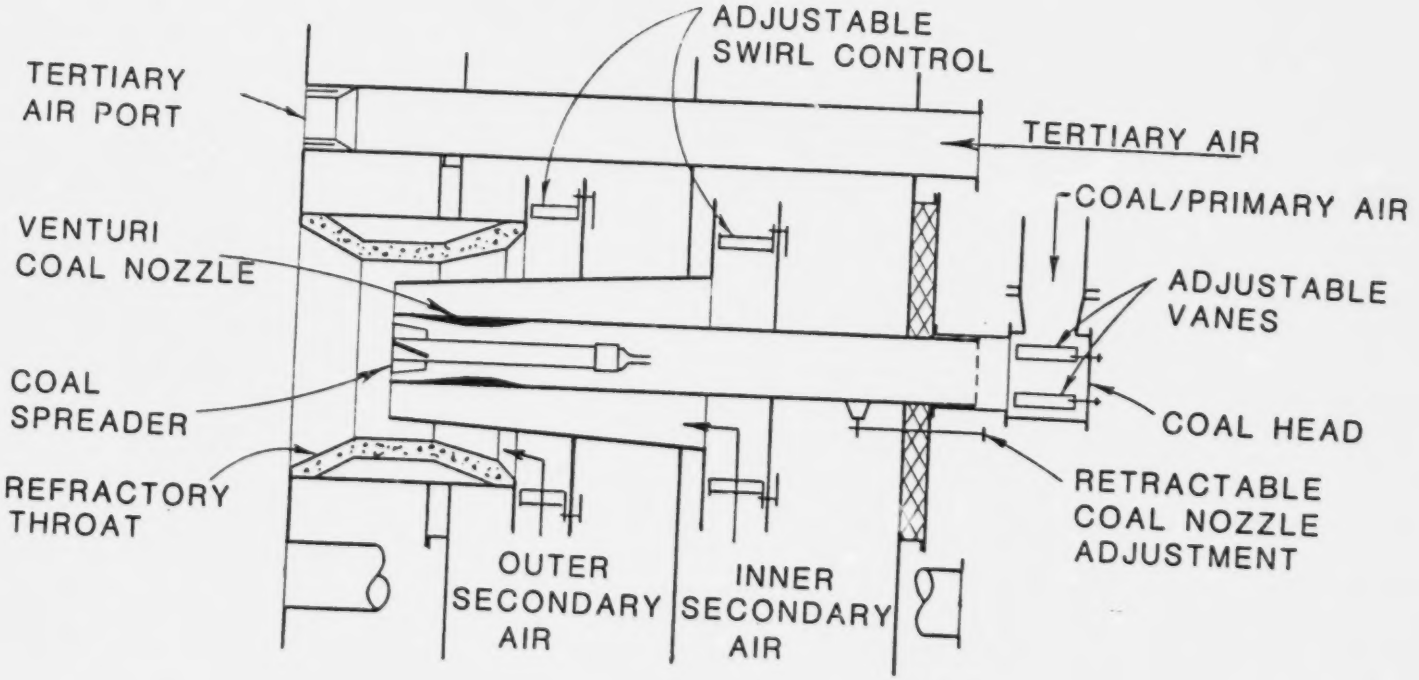


Figure 2-1. Riley Stoker Corporation 100 x 10^6 Btu/hr Distributed Mixing Burner.

horizontal centerline. Both items are commercial systems and enable verification of campatibility of commercial equipment with the prototype DMB.

The RSC DMB design parameters generally match those for the previously tested 50 x 10^6 Btu/hr RSC Low-NO_x burner (see Reference 6) and the EPA DMB design parameters. There are several differences which may be significant. First, the ratio of the radius from the burner centerline to the centerline of the tertiary ports to the throat diameter is 1.80 for the RSC DMB compared to 2.2 as specified by the DMB parameters and 1.44 for the 50 x 10^6 Btu/hr Low-NO_x burner. The ports for the Low-NO_x burner were arranged to minimize the impact on the structural integrity of a boiler's firing face. These differences in the distribution of tertiary air around burner may affect performance. Exit length for the RSC DMB is somewhat longer than for the Low-NO_x burner and should provide for added stability. Inserts of 8-, 10-, and 12-inch diameter permit evaluation of a range of tertiary velocities, which are a factor of 2 to 4 higher than specified by the DMB criteria. These higher velocities should provide for improved flame stability with enhanced mixing by jet entrainment with some sacrifice in NO_x emissions.

The geometry of the secondary air passages for the RSC DMB and the Low-NO_x burner is also different. First, the secondary flow divider setback from the exit differs. The RSC DMB secondary divider setback-to-throat diameter is 0.18, while for the 50 x 10^6 Btu/hr Low-NO_x burner it was 0.24. This difference may offset the mixing and flow patterns. Also, to accommodate the igniter/scanner system, the inner secondary air passage for the RSC DMB is formed by a converging section. The converging section may affect the swirl generated by the register vanes differently than the constant cross-section utilized for the smaller Low-NO_x burner. These hardware differences could be expected to produce different mixing patterns and thus the extrapolation of burner performance, by scaling the results from the Low-NO_x burner to the RSC DMB to field units may not be justifiable.

2.2 Coal Spreader Design

During the optimization of the RSC DMB, several iterative modifications were made in the design of the coal spreader. Previous testing at EER with RSC burners indicated that NO_x emissions could be changed by a factor of two by modifying the spreader design. The first design tested with the RSC DMB was the conically shaped spreader developed for the CCV burner. A sketch of the spreader is shown in Figure 2-2. The remaining spreaders tested were based on a 4-inch diameter support tube. This large diameter body increased the primary velocity through the venturi nozzle thereby concentrating the coal stream and improving the dispersion of the coal with the impeller blades. These designs are summarized in Figure 2-3.

2.3 Fuels and Sorbents

Three different fuels and two sorbents were utilized in the RSC DMB tests. Table 2-1 summarizes the basic compositional analyses of the coals. The Utah coal has been used at the test facility in the development of low-emission, high-efficiency burners. Its characteristics include low sulfur content (0.74 percent, dry) and high-volatile mattter (40.47 percent, dry). Indiana coal has been used as the base fuel in the development of LIMB technology because of its relatively high sulfur content (2.73 percent, dry). The Indiana coal has significantly less volatiles (34.26 percent, dry) than the Utah coal. This difference would test the applicability of the DMB to various coals. The Illinois coal, from the Crown 1I mine in Virden, Illinois, is the coal burned at CILCO Duck Creek Station. The CILCO station was the basis for previous studies at EER of RSC burners and the use of the Illinois coal will permit extrapolation of test results in EER's facilities to an operating utility boiler. The Illinois coal has a high sulfur content (3.97 percent, dry) and provides the opportunity to evaluate LIMB technology for high sulfur fuels. The bowl mill utilized for these tests pulverized each of the three coals to acceptable fineness (70 percent through 200 mesh). The range of fineness achieved during the tests is listed in Table 2-2.

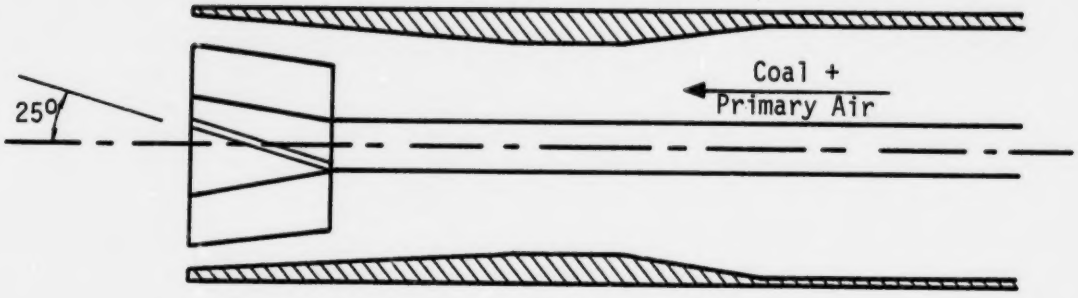
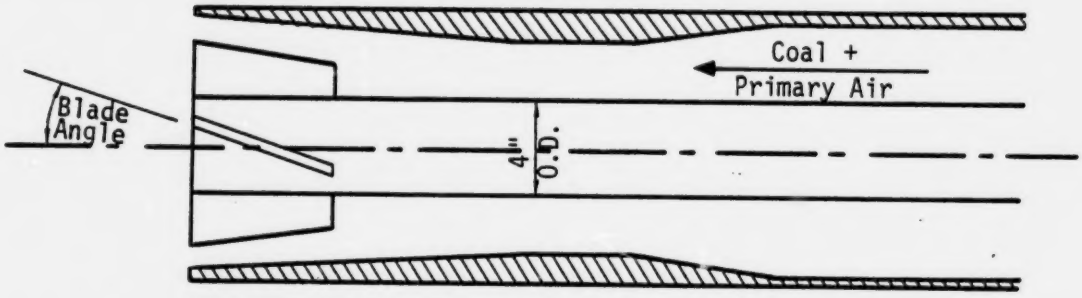


Figure 2-2. Spreader #1--Controlled Combustion Venturi spreader for Riley Stoker Corporation Distributed Mixing Burner.



Spreader Design	Number of Blades	Blade Angle	Blade Length
2	4	15°	Long
3	4	35°	Long
4	4	35°	Short
5	4	28°	Short

Figure 2-3. Impeller designs based on 4-in. support tube for Riley Stoker Corporation Distributed Mixing Burner.

TABLE 2-1. SUMMARY OF COAL COMPOSITION

Reporting Basis >	Utah Coal		Indiana Coal		Illinois Coal	
	As Rec'd.	Dry	As Rec'd.	Dry	As Rec'd.	Dry
Proximate (% Wt)						
Moisture	5.46	0.00	7.75	0.00	10.66	0.00
Ash	10.00	10.57	9.17	9.94	9.37	10.49
Volatile	38.26	40.47	31.60	34.26	34.51	38.62
Fixed C	46.28	48.96	51.48	55.80	45.46	50.89
Total	100.00	100.00	100.00	100.00	100.00	100.00
Sulfur	0.70	0.74	2.52	2.73	3.54	3.97
Btu/Lb	11930	12619	11498	12465	11265	12609
MMF Btu/Lb		14269		14048		14349
MAF Btu/Lb		14111		13841		14086
Ultimate (% Wt)						
Moisture	5.46	0.00	7.75	0.00	10.66	0.00
Carbon	67.59	71.50	66.42	72.00	61.99	69.38
Hydrogen	5.09	5.38	4.56	4.95	4.54	5.08
Nitrogen	1.21	1.28	1.10	1.19	0.96	1.08
Sulfur	0.70	0.74	2.52	2.73	3.54	3.97
Ash	10.00	10.57	9.17	9.94	9.37	10.49
Oxygen	9.95	10.53	8.48	9.19	8.94	10.00
Total	100.00	100.00	100.00	100.00	100.00	100.00
Elemental Ash (% Wt)						
SiO_2		66.17		43.08		49.45
Al_2O_3		16.49		23.79		17.28
TiO_2		0.68		0.49		0.68
Fe_2O_3		4.95		27.85		18.41
CaO		3.72		1.16		4.33
MgO		0.87		0.20		0.83
Na_2O		1.27		0.17		1.40
K_2O		2.11		0.65		2.15
P_2O_5		0.30		0.22		0.18
SO_3		3.07		0.19		4.31

TABLE 2-2. SUMMARY OF COAL FINENESS

Coal Type	Range of Size Distribution (% Through 200 Mesh)	Mean	Standard Deviation
Utah	61.0 - 77.2	71.32	3.93
Indiana	70.6 - 72.4	71.57	0.91
Illinois	69.3 - 72.0	70.65	1.91

The two sorbents used for the evaluation of SO_2 reduction potential were a pre-ground limestone material (Vicron 45-3) and a pre-ground, processed hydrated lime. These two materials represent high-purity calcium-based sorbent materials. Their characteristics are listed in Table 2-3. The Vicron 45-3 is 98 percent pure $CaCO_3$, while the Colton hydrated lime is 90.5 percent $Ca(OH)_2$. Mass median particle diameters were 11 μm and 7 μm, respectively.

2.4 Test Facilities and Procedures

The RSC DMB was tested in the EPA LWS at EER's test site. The LWS is a 150×10^6 Btu/hr combustor test facility, shown schematically in Figure 2-4. The furnace is designed to match the size and geometry of a large industrial or small utility single wall-fired boiler. The LWS characteristics are detailed in Table 2-4.

Test procedures applied to these tests were grouped in two formats as listed in Tables 2-5 and 2-6.

- Standard Measurement Format--routine measurements applied to all test conditions.

- Detailed Measurement Format--additional measurements applied to specific test conditions to more fully characterize burner performance.

The burner variables tested were load, excess air, burner settings, and sorbent feed rate and injection location, in accordance with the matrix outlined in the Measurement Plan (MP). Specific tests each day were determined to most efficiently characterize the effect of these variables on burner performance. Test procedures utilized were in accordance with the Quality Assurance Program Plan (QAPP). Specific Quality Assurance activities are described in Appendix A.

TABLE 2-3. SORBENT CHARACTERISTICS

Sorbent	Theoretical Character-istics	Physical Properties				Chemical Analysis (% Weight)							
		Mean Size (μm)	Density (gm/cm^3)	Surface Area (m^2/gm)	Ignition Loss (% Wt.@ 2000°F)	Ca	Fe	Al	Na	Mg	K	Si	Cr
Vicron 45-3	$CaCO_3$	11.0	2.757	0.9	44.0	39.2	0.037	0.07	0.022	0.485	0.011	0.07	0.006
Hydrated Lime	$Ca(OH)_2$	7.0	2.353	10.4	26.4	48.9	0.164	0.28	0.034	0.255	0.129	1.08	0.005

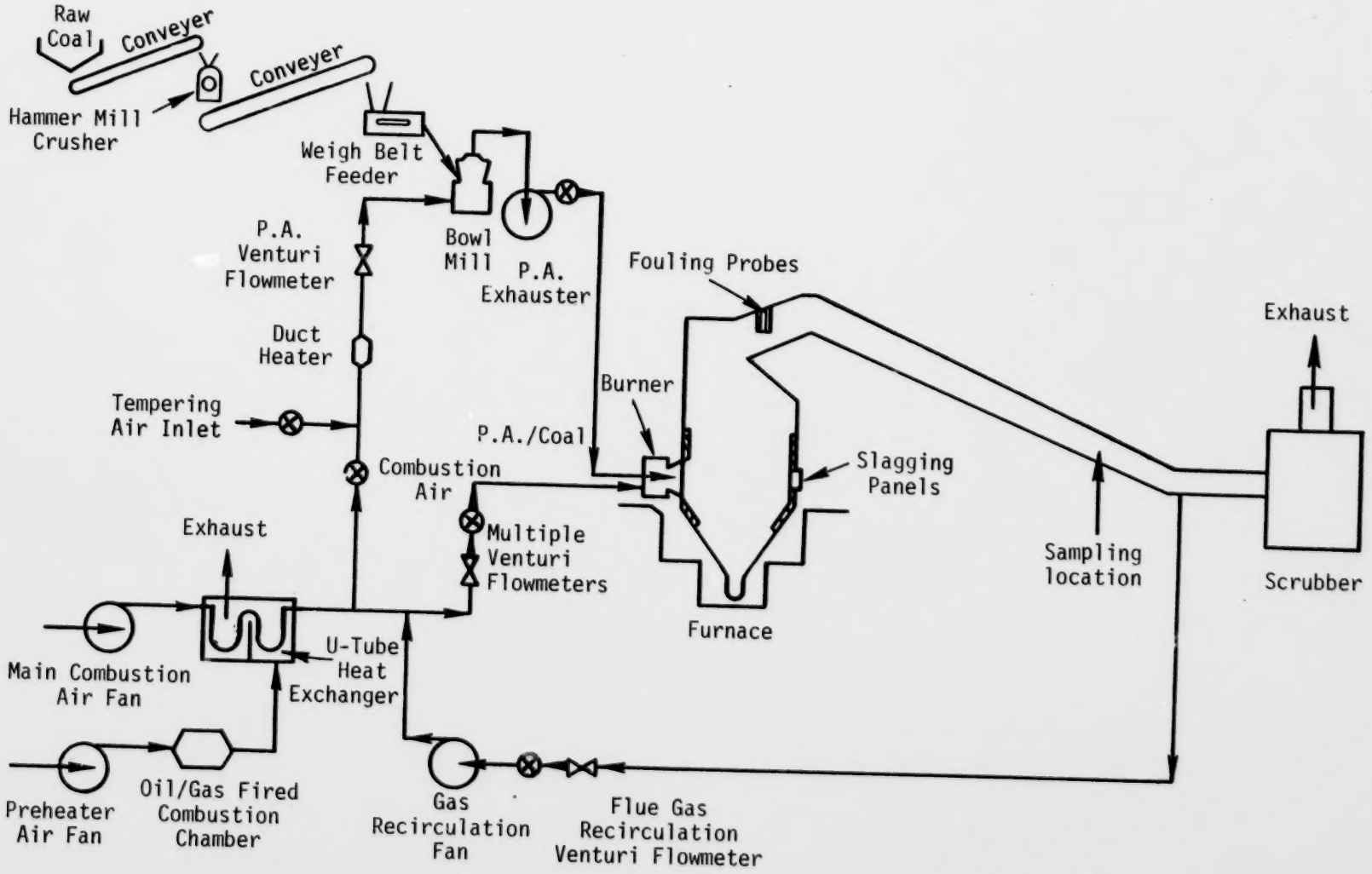


Figure 2-4. Large watertube boiler simulator system schematic.

TABLE 2-4. LWS FURNACE CHARACTERISTICS

Parameter		Value
Firing		
Configuration	Primary	Single Wall
	Optional	Opposed or Corner
Firing Rate	Minimum	50×10^6 Btu/hr (Practical Limit)
	Maximum	150×10^6 Btu/hr
Dimensions		
Firing Depth		22 ft
Width		16 ft
Rear Wall Height		20 ft
Knuckle-to-Nose Height		27.5 ft
Nose Angle		37^o (From Horizontal)
Hopper Angle		52^o (From Horizontal)
Height Above Ground Level		35.7 ft
Total Vertical Height		50.5 ft (Pit-to-Top)
Cooled Surface Area		
Burner Zone		704 ft^2
Total Furnace		1951 ft^2
Volume		
Burner Zone		3520 ft^3
Total Furnace		11,544 ft^3 (to Nose)
Insulation		All Sidewalls Knuckle-Up 16 ft.
Cooling		Spray-Cooled on All Surfaces

TABLE 2-5. STANDARD MEASUREMENT FORMAT

Inputs			Outputs		
Parameter	Method	Record	Parameter	Method	Record
Burner Settings	Manual	Manual	Flame Characteristics	Manual and Color Video	Manual
Air Flow Rates	Venturis	Computer			
Air Temperature	Thermocouples	Computer	Combustion Products:		
			O_2	Taylor, Paramagnetic	
Coal Flow Rate	Weigh Belt Feeder and Calculation from Coal Composition, Air Flow and Excess O_2	Computer	CO	Anarad, NDIR	Computer and Strip Chart Recorder
			CO_2	Anarad, NDIR	
Sorbent Injection Location	Manual	Manual	NO_x	TECO, Chemiluminescent	
Sorbent Flow Rate	Volumetric Feeder	Manual	SO_2	TECO, Pulsed Fluorescence	
Ambient Humidity	Sling Psychrometer	Manual	Burner/Furnace Pressures	Magnehelics	Manual
			Furnace Temperatures	Thermocouples	Computer

TABLE 2-6. DETAILED MEASUREMENT FORMAT

Inputs		Outputs	
Parameter	Method	Parameter	Method
Coal Composition	Ultimate and proximate analysis - ASTM	Particulate Matter: Total mass	EPA Method 5
		Composition	Ultimate analysis-ASTM
Coal Size Distribution	ASTM Method D197		
Sorbent Composition	ASTM Methods	Carbon Balance:	
		CO, CO_2	Standard Measurement Format
		Hydrocarbons	Continuous Monitor FID
Sorbent Size Distribution	ASTM sieve analysis	Particulate	Ultimate analysis
		Bottom Ash	Grab sample and ultimate analysis
		Sulfur Balance:	
		SO_2	Continuous Monitor UV and/or EPA Method 6
		SO_3	Controlled Condensation and EPA Method 8
		Particulate	Ultimate analysis
		Bottom Ash	Grab sample and ultimate analysis

3.0 NO_x AND PERFORMANCE OPTIMIZATION OF THE RILEY STOKER CORPORATION DMB

The design of the RSC DMB incorporated a large number of variables to permit flexibility in achieving optimum NO_x performance. The adjustable burner components included:

1. Retractable coal spreader.
2. Telescoping RSC venturi coal nozzle.
3. Two parallel secondary air registers for swirl control.
4. Divided windbox for independent flow control to secondary air passages.
5. Removable inserts for tertiary air velocity control.

Previous testing of RSC burners in EER test facilities indicated that coal spreader design had a pronounced effect on burner performance and was a sixth variable considered in optimization of the DMB.

Burner performance was evaluated according to the following criteria.

1. Low NO_x emissions.
2. Low CO emissions over a wide range of excess air.
3. Low carbon loss in the fly ash.
4. Stable flame over a wide operating rane.
5. Low burner head pressure.
6. Short, compact flames.

3.1 Initial Performance Optimization With Utah Coal

The RSC DMB was first equipped with the coal nozzle/spreader configuration developed as part of the RSC CCV burner. Figure 3-1 summarizes the unstaged performance with this spreader. NO_x emissions were low 202 ppm*

*All gas concentrations in this report corrected to 3 percent O_2.

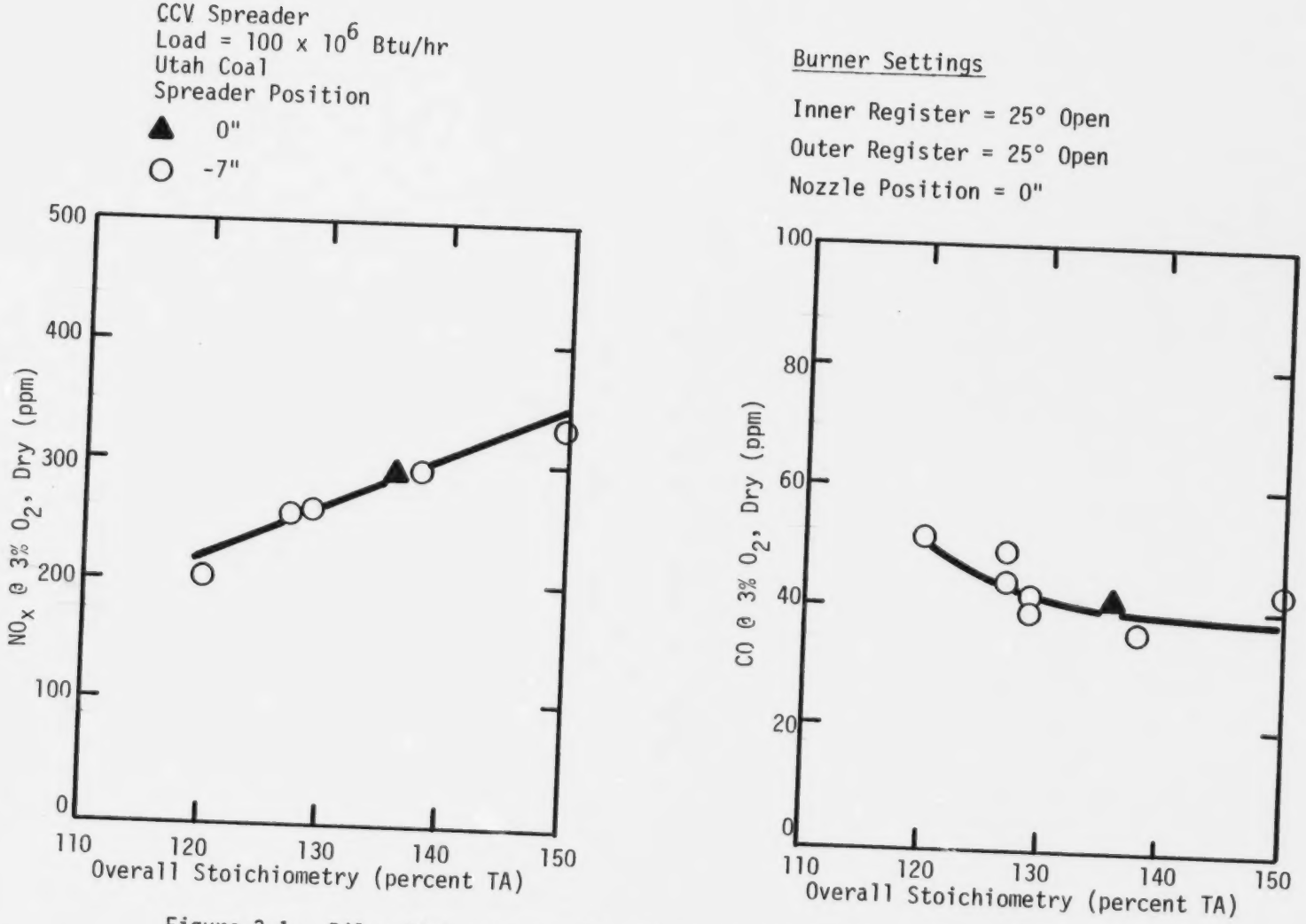


Figure 3-1. Riley Stoker Corporation DMB unstaged performance with CCV spreader.

with 51 ppm* CO at 20 percent excess air. The flame producing these low emissions was long, impinging on the rear wall 22 feet from the burner exit. Fly ash collected during these unstaged tests contained over 17 percent carbon in the ash, an indication of poor performance. The Low-NO_x emissions and high carbon in the ash indicate that the long flame impinging on the relatively cold rear wall of the LWS was in effect quenched. The burner variables, such as spreader position, did not significantly affect performance. The range of register positions for stable performance was observed to be very narrow, with positions greater than about 30° open resulting in the flame lifting off the burner exit.

The long flame produced from the first spreader configuration was unacceptable for testing in the LWS. A second spreader design, with 4 blades set at a 15° angle from axial on a 4-inch pipe, was selected to increase the velocity of the primary air and coal through the venturi nozzle, and thus increase the mixing induced by the spreader vanes. The increased swirl of the primary air and coal did improve mixing and produced a significantly shorter unstaged flame. Flame length was reduced from over 22 feet long to only 12-14 feet. NO_x emissions under unstaged conditions increased to 240-270 ppm. Carbon content of fly ash samples was about 5.9 percent, much lower than achieved with the CCV spreader. Figure 3-2 illustrates the effect of register position on unstaged performance, especially flame characteristics. The ignition point of the flame lifted from the burner exit with register positions more than 30° open. When the registers were opened to 35°, the base of the flame was observed to lift off the exit from its normal stable operating point, rooted well into the burner exit, to an estimated 7 feet from the firing face.

Diversion of combustion air to the 12-inch diameter tertiary air ports produced the staged performance summarized in Figure 3-3. Initial staging was done with the registers at 15° open; however, it was necessary to close both registers to 20° open to maintain stability at burner zone stoichiometries (SR_B) less than 90 percent theoretical air (TA). NO_x was reduced from

*All gas concentrations in this report corrected to 3 percent O_2.

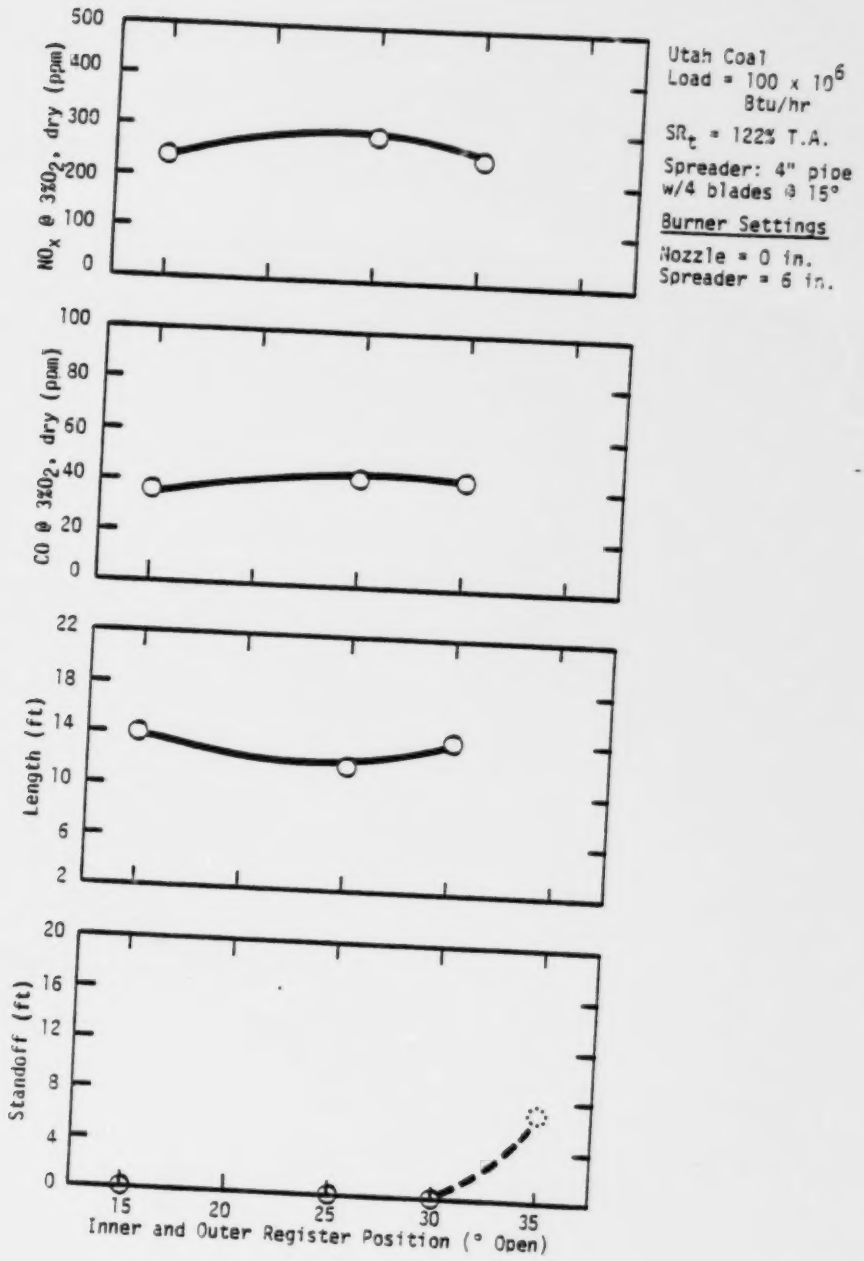


Figure 3-2. Effect of register position on unstaged performance with Spreader #2 and 12" tertiary ports.

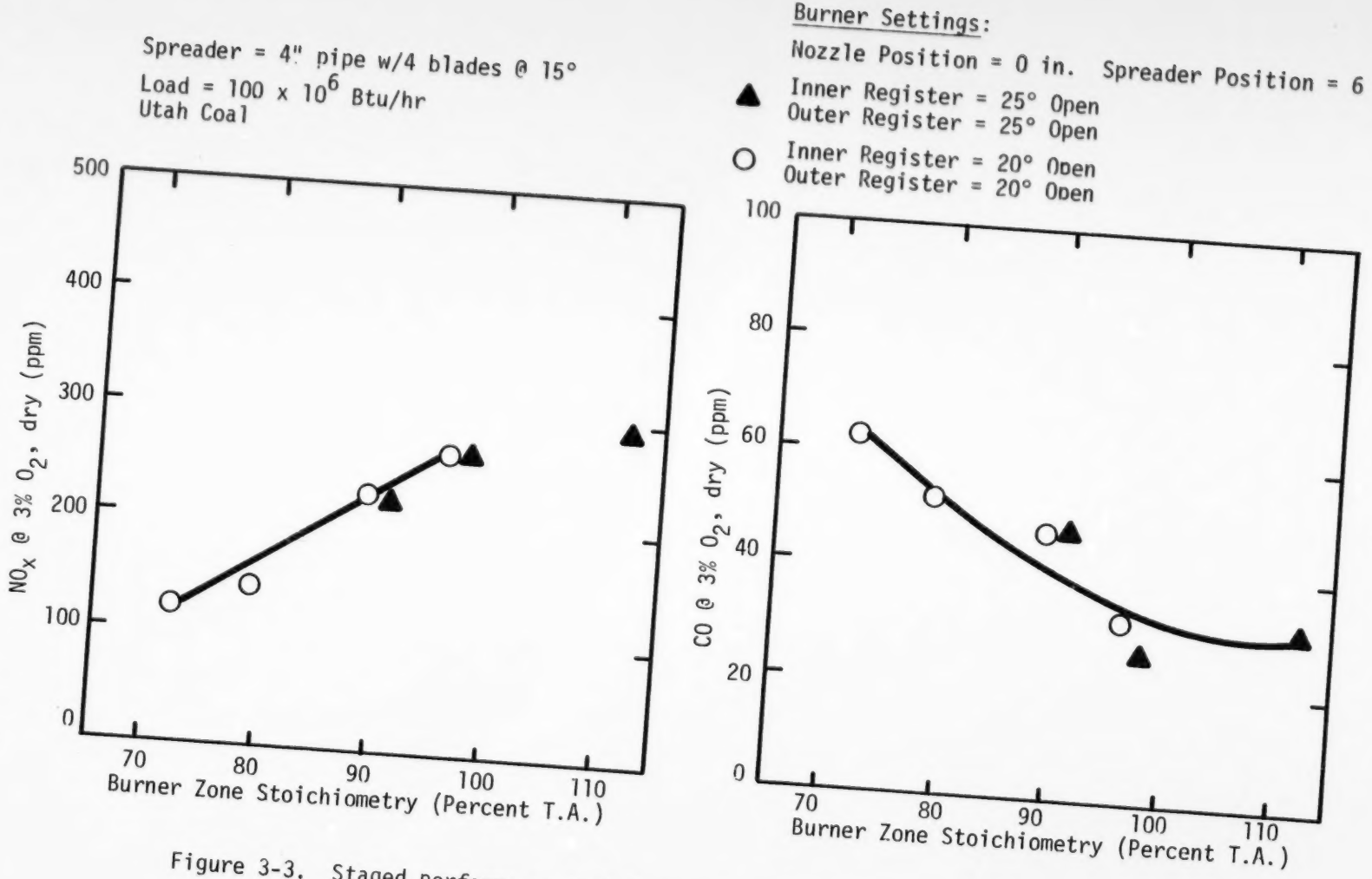

Spreader = 4" pipe w/4 blades @ 15°
Load = 100 x 10^6 Btu/hr
Utah Coal
Burner Settings:
Nozzle Position = 0 in. Spreader Position = 6 in.
Inner Register = 25° Open
Outer Register = 25° Open
Inner Register = 20° Open
Outer Register = 20° Open
NOx @ 3% O2, dry (ppm)
CO @ 3% O2, dry (ppm)
Burner Zone Stoichiometry (Percent T.A.)
Burner Zone Stoichiometry (Percent T.A.)

Figure 3-3. Staged performance with Spreader #2 and 12-in. tertiary ports.

about 290 ppm unstaged to 123 ppm at a burner zone stoichiometry of 72 percent. CO, an indication of combustion efficiency, gradually increased from 30 ppm unstaged to over 60 ppm. Analysis of fly ash at the staged condition yielded about 22 percent carbon. Flame length increased to over 22 feet, with flame impinging on the rear wall of the furnace. This impingement again caused a quenching effect, suppressing NO_x formation and decreasing combustion efficiency.

Previous tests have shown that increasing tertiary air velocities tend to decrease flame length. Increasing the tertiary air velocities increases the mixing of the tertiary air jet with the flame by entrainment. Inserts were installed in the tertiary air ports to decrease the diameter from 12 inches to 8 inches. This resulted in increasing the tertiary velocity by a factor of 2.25. The length of the staged flame was shorter, with no flame impingement on the rear wall observed. As a result of the increased mixing, NO_x emissions increased to 166 ppm and the CO level was reduced to 36 ppm. The effect of tertiary port size and velocity is summarized in Figure 3-4.

The distribution of secondary air between the inner and outer passages was evaluated for optimum performance. The results are presented in Figure 3-5. Biasing the secondary air to the inner passage resulted in lower NO_x emissions as well as lengthening the flame such that it impacted the rear wall. Bias toward the outer secondary air passage also increased flame length but had no significant effect on emissions. Optimum flame length was achieved with an equal distribution of air to the parallel secondary air passages.

The position of the venturi nozzle was varied while maintaining the spreader in the same relative position, 6 inches back in the venturi. Table 3-1 summarizes the effects observed. The optimum position for this Spreader #2 design was -2 inches from baseline position. All other positions appeared to result in flames measurably longer and definitely impacting the rear wall.

The staged performance of the RSC DMB with Spreader #2 and 8-in. tertiary ports at optimum burner settings is presented in Figures 3-6 and 3-7. Staging down to a burner zone stoichiometry of 70 percent TA from

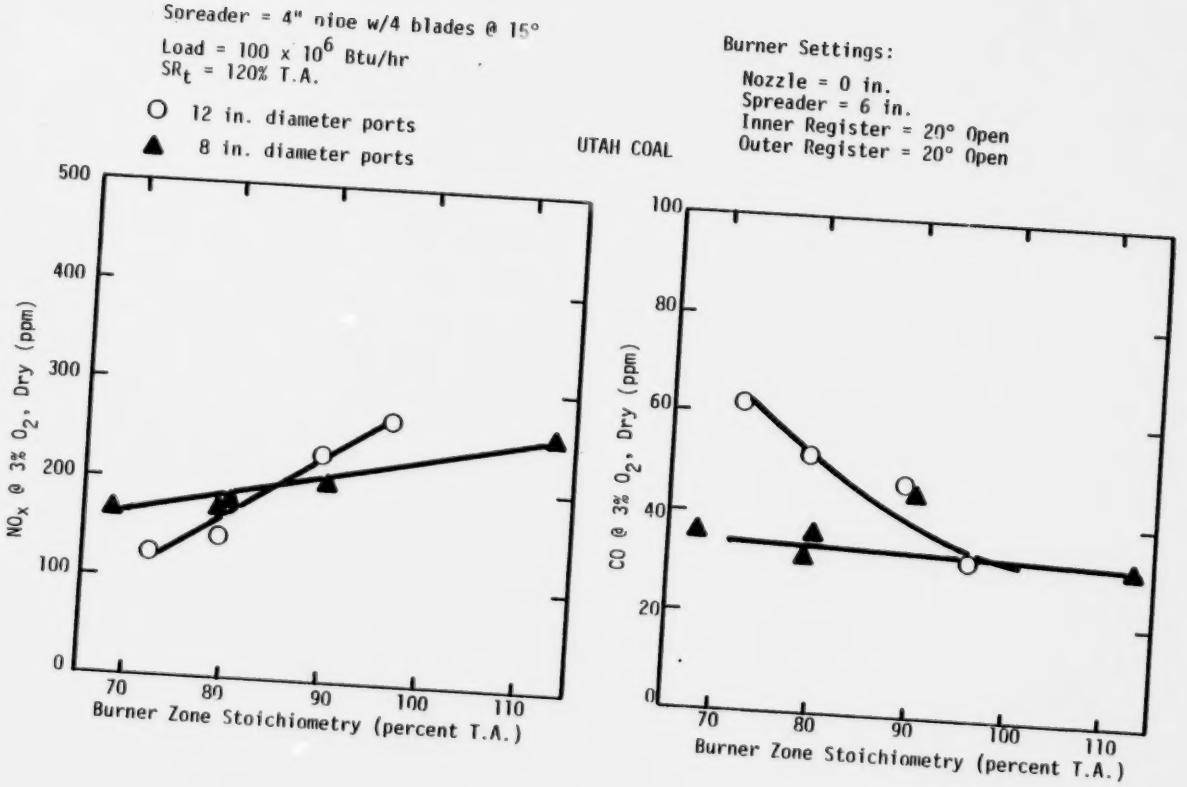

Spreader = 4" nipe w/4 blades @ 15°
Load = 100 x 10^6 Btu/hr
SR_t = 120% T.A.
12 in. diameter ports
8 in. diameter ports
UTAH COAL
Burner Settings:
Nozzle = 0 in.
Spreader = 6 in.
Inner Register = 20° Open
Outer Register = 20° Open
NOx @ 3% O2, Dry (ppm)
CO @ 3% O2, Dry (ppm)
Burner Zone Stoichiometry (percent T.A.)
Burner Zone Stoichiometry (percent T.A.)

Figure 3-4. Effect of tertiary velocity on Riley Stoker Corporation DMB staged performance with Spreader #2.

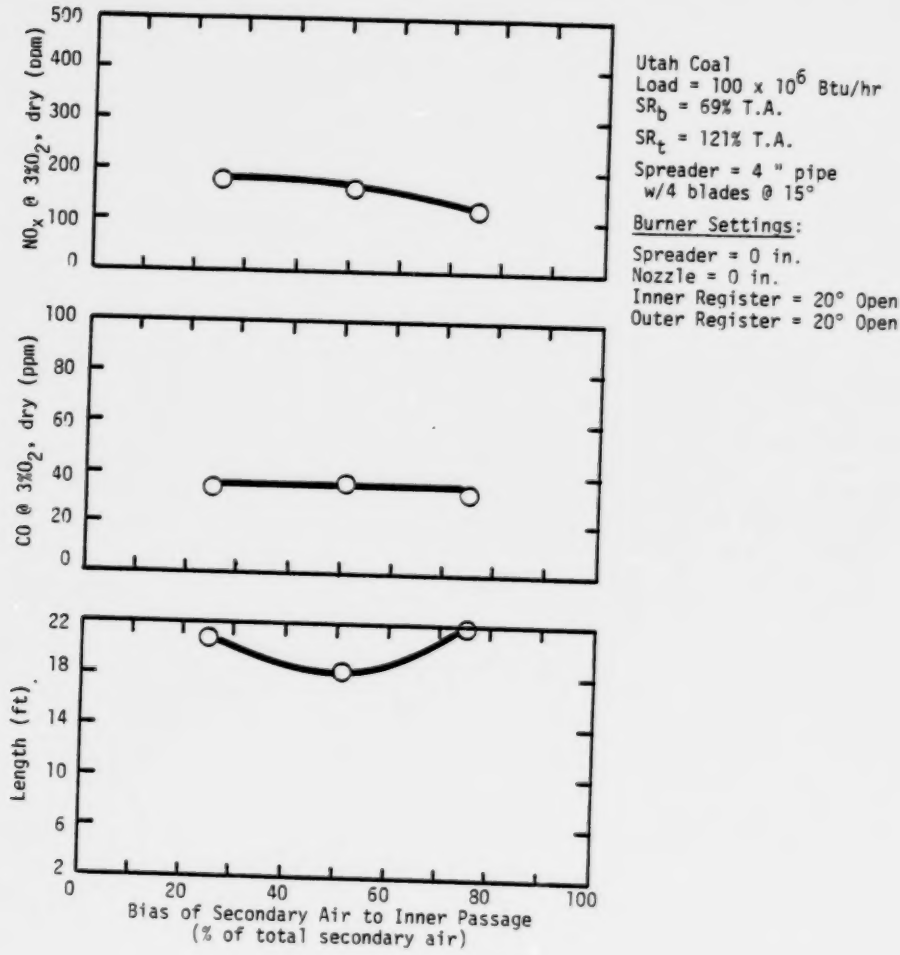


Figure 3-5. Effect of secondary air distribution on staged performance with Spreader #2 and 8-in. tertiary ports.

TABLE 3-1. SUMMARY OF THE EFFECT OF NOZZLE POSITION ON RILEY STOKER CORPORATION DMB PERFORMANCE WITH SPREADER #2 AT 6-IN. AND 8-IN. TERTIARY PORTS

Nozzle Position (in.)	NO_x @ 3% O_2 (ppm)	Flame Characteristics
-2	169	~21 ft. long. No observed impingement.
-3	96	Unstable, flame > 22 ft. long. Flame impinging on rear wall.
+1	125	Flame > 22 ft. long. Flame impinging on rear wall.

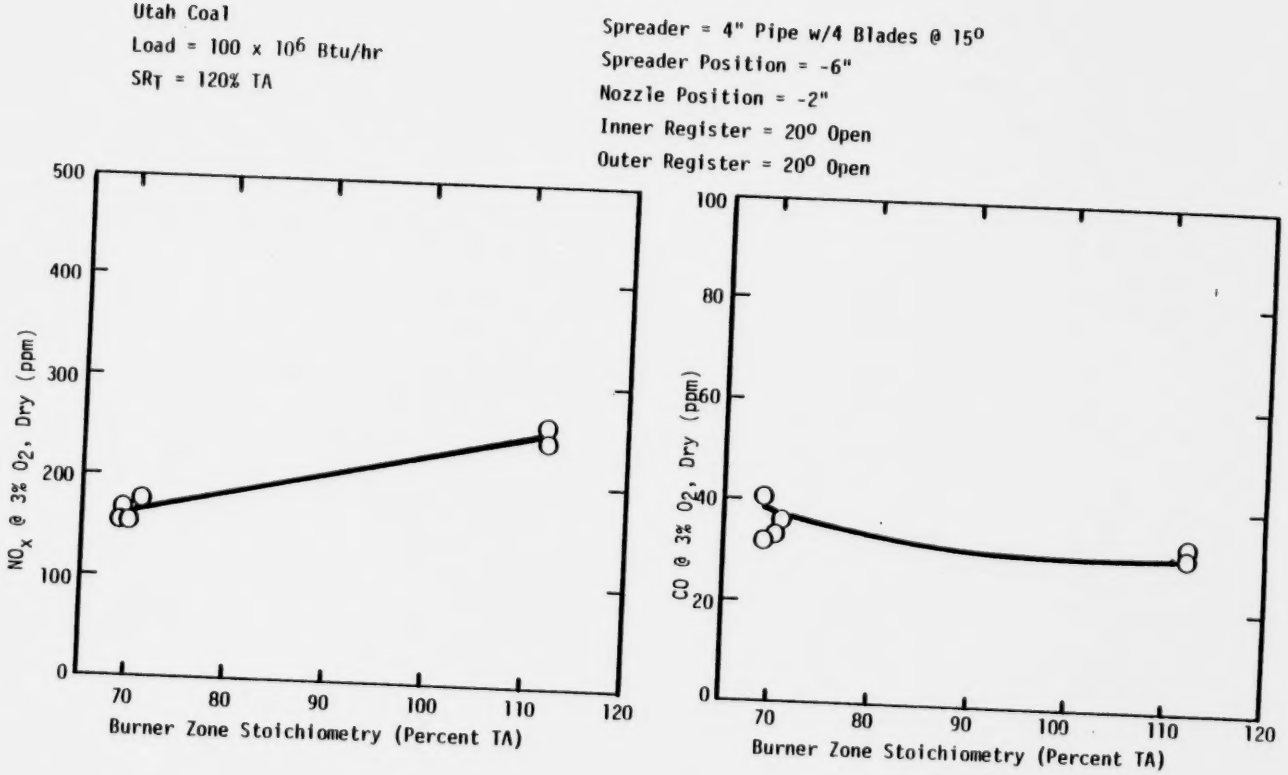


Figure 3-6. Staged performance with Spreader #2 and 8" tertiary ports.

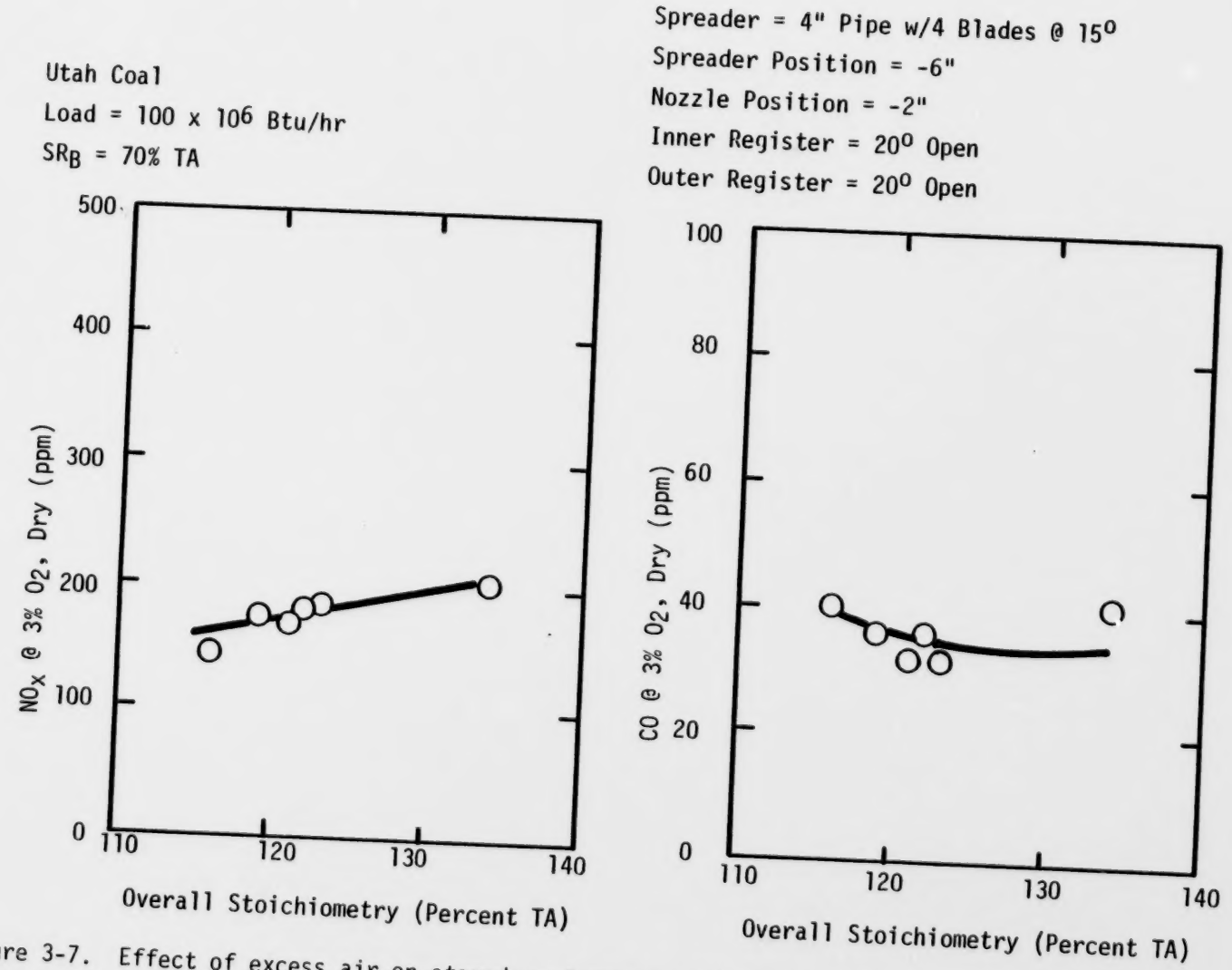


Figure 3-7. Effect of excess air on staged performance with Spreader #2 and 8-in. tertiary ports.

unstaged conditions reduced NO_x by 37 percent. Low levels of NO_x were achieved while maintaining low CO down to 15 percent excess air. Analysis of fly ash samples at these optimum conditions yielded about 22 percent carbon. This indicated that although visual observations showed no indication of impingement in sighting through the viewports, the flame may yet have been hitting the rear wall out of the angle of view.

3.2 Additional Developmental Optimization for Indiana and Illinois Coals

Acceptable flame length and stability could not be achieved when the Indiana coal was first fired in the RSC DMB in the configuration found to give good performance with the Utah coal. Figure 3-8 summarizes adjustments in nozzle and spreader positions in trying to achieve acceptable performance. The principle reason for the difference in performance between the Utah and Indiana coals appears to be due to significantly less volatiles in the Indiana coal (34.26 percent) than in the Utah coal(40.47 percent). Since burner adjustments did not significantly improve burner performance, the spreader design was iteratively modified to achieve acceptable flame length, coal head pressure, and stability.

The spreader modifications involved altering blade positions and lengths using the 4-inch pipe of Spreader #2 as the support tube, with the objective to improve mixing of the primary air and coal with the secondary air. Table 3-2 summarizes the development of the spreaders. The first modification, Spreader #3, increased the angle of the blades from 15^o to 25^o. The resulting coal spreader produced a coal head pressure of over 14 in. H_2O and low primary velocity. It also caused combustion products to blow back through the spreader support pipe, which was uncapped and open to facilitate insertion of the oil gun throughout all the tests. To try to decrease the coal head pressure and blow back of combustion products, the length of the Spreader #3 blades was reduced. When fired, the resulting Spreader #4 did not improve performance. The coal head pressure remained excessively high at all spreader positions. The next modification was to reposition the blades of Spreader #4 for a 28^o angle. This spreader achieved acceptable

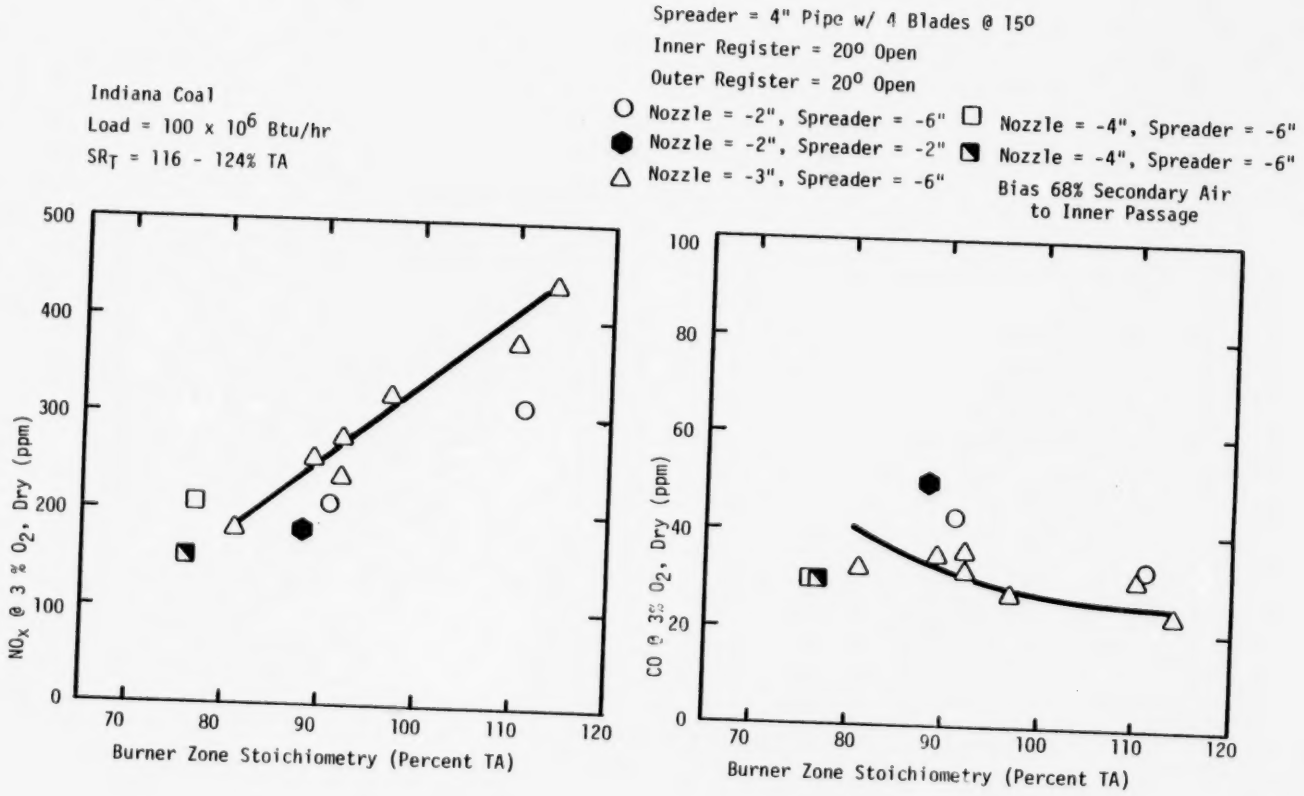

Spreader = 4" Pipe w/ 4 Blades @ 15°
Inner Register = 20° Open
Outer Register = 20° Open
Indiana Coal
Load = 100 x 10^6 Btu/hr
SR_T = 116 - 124% TA
Nozzle = -2", Spreader = -6"
Nozzle = -2", Spreader = -2"
Nozzle = -3", Spreader = -6"
Nozzle = -4", Spreader = -6"
Nozzle = -4", Spreader = -6"
Bias 68% Secondary Air to Inner Passage
NOx @ 3 % O2, Dry (ppm)
CO @ 3% O2, Dry (ppm)
Burner Zone Stoichiometry (Percent TA)
Burner Zone Stoichiometry (Percent TA)

Figure 3-8. Effect of Spreader #2 and nozzle position on Riley Stoker Corporation DMB performance with Indiana coal.

TABLE 3-2. ITERATIVE DEVELOPMENT OF RILEY STOKER CORPORATION COAL SPREADERS FOR INDIANA COAL FIRING

Spreader Design	Performance Characteristics
#2: 4-in. pipe with four long blades @ 15°	Flame length > 22 ft.
#3: 4-in pipe with four long blades @ 35°	High coal head pressure (> 14-in. H_2O) resulting in low primary velocity. Combustion products blow back through spreader support pipe.
#4: 4-in. pipe with four short blades @ 35°	Coal head pressure still too high (14-in. H_2O)
#5: 4-in pipe with four short blades @ 28°	Acceptable coal head pressure. Flame length 19-20 ft. under staged conditions.

performance, with stable flames under staged conditions and flame length between 19 and 20 feet.

The range of burner adjustments that maintained flame stability was limited (e.g., register vane position 20° open or less). Figure 3-9 summarizes the staged performance with Spreader #5. NO_x emissions were substantially higher (230 ppm) than those produced by Spreader #2 with Utah coal (165 ppm). CO levels were comparable, but more importantly, there was a significant improvement in carbon burnout. No problems were experienced when the Illinois coal was fired with Spreader #5. Flame stability at low load actually improved over the Indiana coal, due in part to the higher volatile matter content (38.62 percent) of the Illinois coal. The Utah coal was retested using the Spreader #5 configuration with improved performance. Although NO_x emissions increased at the design point from 165 ppm to 200 ppm, flame length was signifi.antly shorter and the carbon content of the fly ash was reduced from 22 percent to about 10 percent. NO_x emissions from the Utah coal were comparable to NO_x levels measured during tests of the other two fuels with Spreader #5, as shown in Figure 3-9. The effect of excess air on NO_x and CO emissions is summarized in Figure 3-10. The emissions from the three fuels fall within a range of 40 ppm with an average slope of approximately 4 ppm/percent TA. The RSC DMB was able to operate over a wide range of excess air, with transient data indicating that the rapid rise of CO emissions occurs at about 10 percent excess air.

The carbon content of the ash gives a relative indication of burner efficiency. Carbon burnout, C_b, can be defined as:

$$C_b = \left[1 - \frac{\left(\frac{Cp}{Ap}\right)}{\left(\frac{Cc}{Ac}\right)}\right] \times 100\%$$

where Cp = percent carbon in particulate matter
Ap = percent ash in particulate matter
Cc = percent carbon in coal
Ac = percent ash in coal

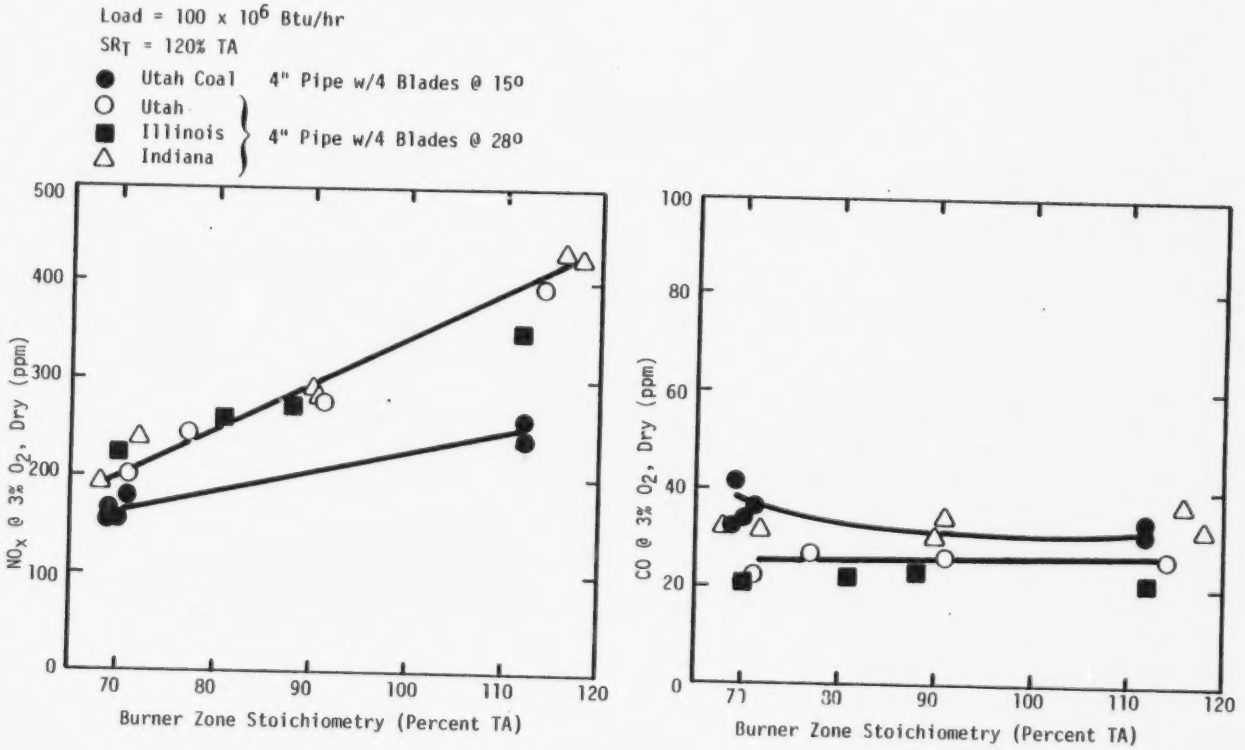

Load = 100 x 10^6 Btu/hr
SR_T = 120% TA
Utah Coal
Utah
Illinois
Indiana
4" Pipe w/4 Blades @ 15°
4" Pipe w/4 Blades @ 28°
NOx @ 3% O2, Dry (ppm)
CO @ 3% O2, Dry (ppm)
Burner Zone Stoichiometry (Percent TA)
Burner Zone Stoichiometry (Percent TA)

Figure 3-9. Summary of Riley Stoker Corporation DMB performance.

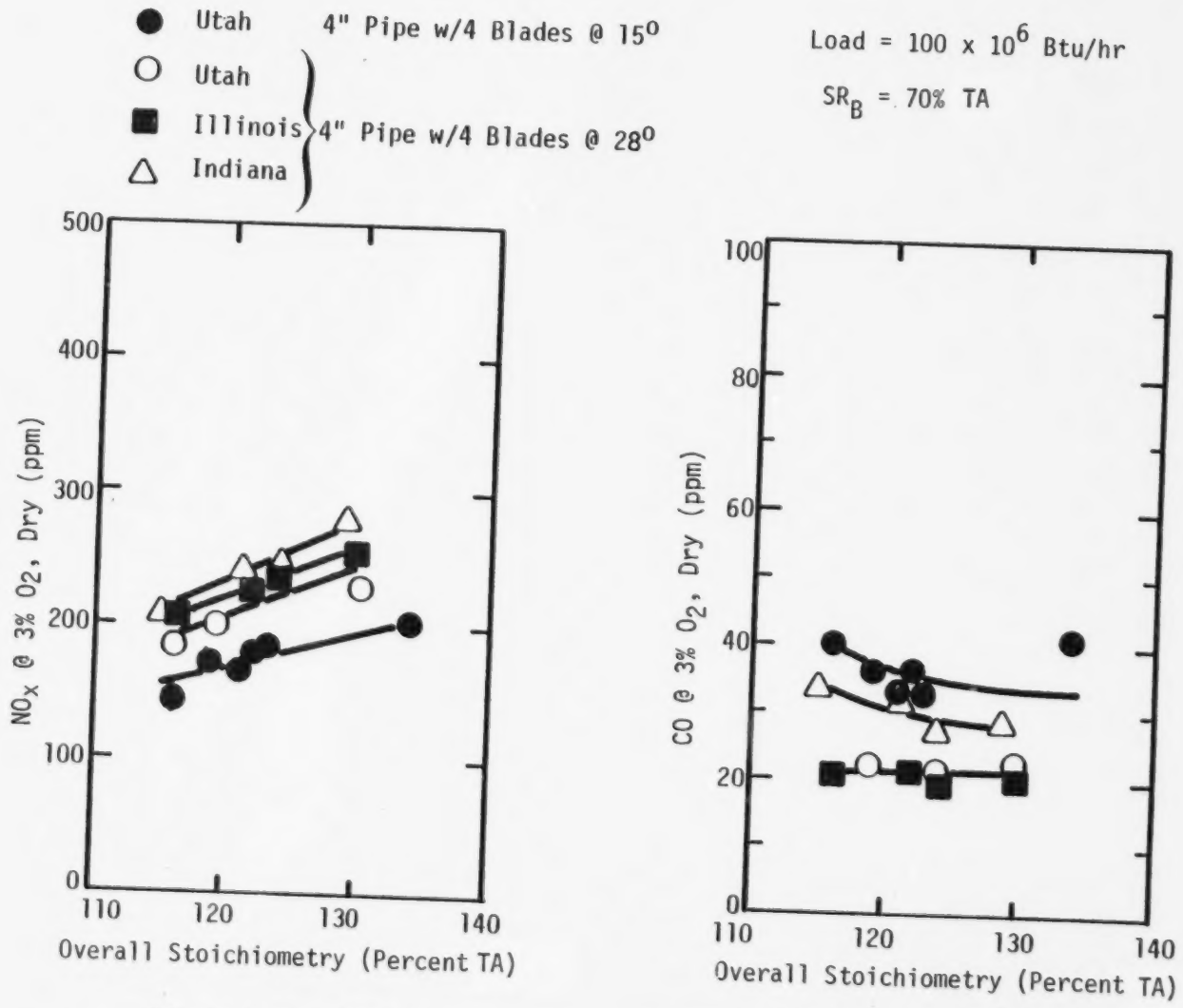


Figure 3-10. Effect of excess air on Riley Stoker Corporation Distributed Mixing Burner emissions.

Using this definition, the carbon burnout improved with the change in spreader design for the Utah coal, increasing from 95.9 percent to 98.3 percent for staged operation. Burnout for the Indiana and Illinois coals was also high for staged conditions, 98.8 and 99.0 percent respectively.

The ability to reduce the burner load, or turndown capability, was evaluated for each coal with the final spreader configuration. The results are presented in Figure 3-11. With the Utah and Illinois coals, it was possible to maintain stable staged operation (SR_B = 70 percent TA) down to 60 percent of full load. For the Indiana coal, it was necessary to decrease staging to a burner zone stoichiometry of 90 percent TA for stable operation at 60 x 10^6 Btu/hr. For each coal, firing rate had small effect on NO_x emissions. NO_x emissions decreased between 10 and 16 percent when the firing rate was decreased from 100 x 10^6 Btu/hr to 60 x 10^6 Btu/hr. Combustion efficiency, as indicated by CO levels, did not change significantly.

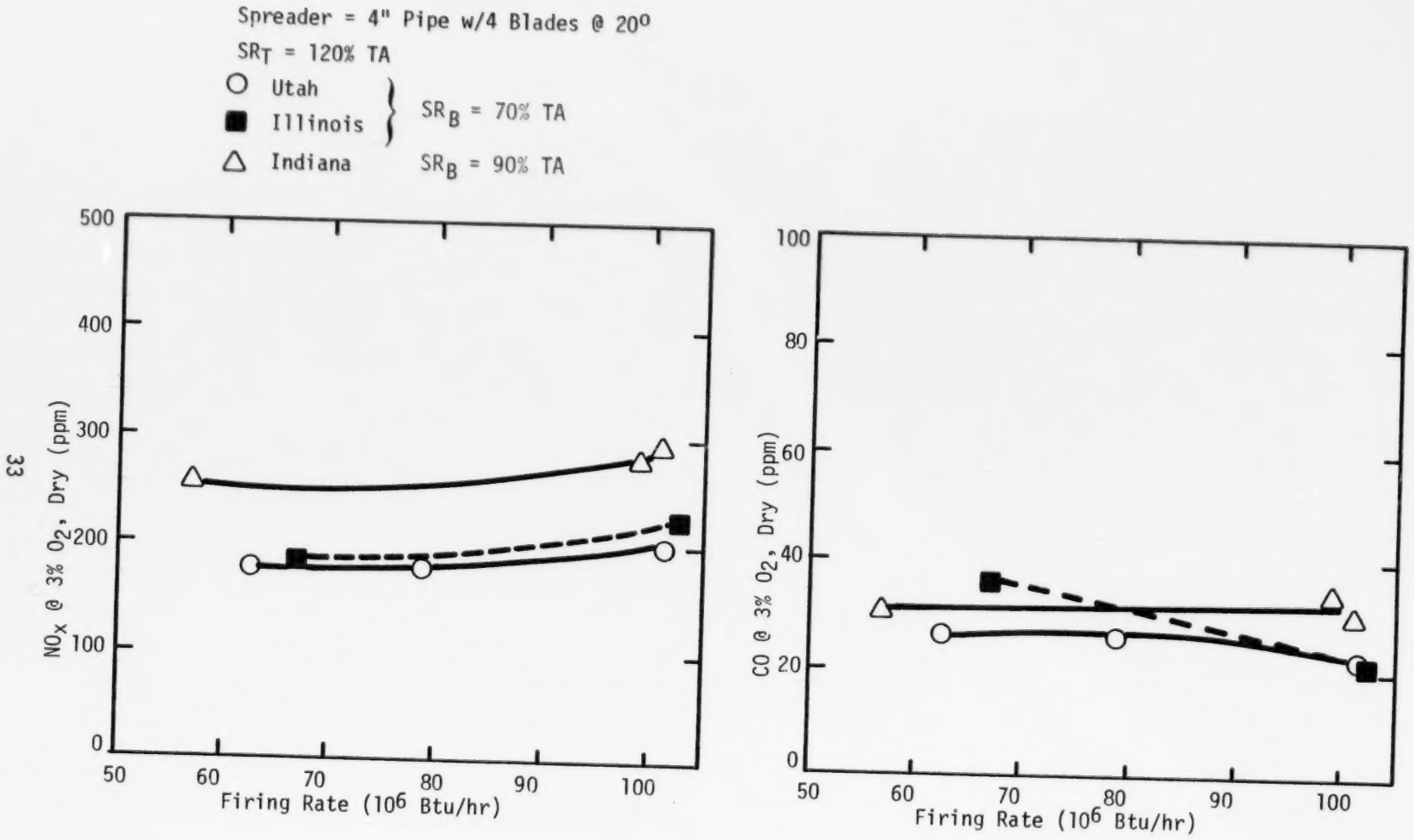


Figure 3-11. Effect of load on Riley Stoker Corporation Distributed Mixing Burner emissions with optimized spreader.

4.0 SULFUR DIOXIDE REDUCTION POTENTIAL WITH SORBENT INJECTION

The LIMB (Limestone Injection Multistage Burner) concept for SO_2 reduction was evaluated with the RSC DMB by the addition of sorbent materials. This was accomplished by injecting the sorbent with the coal or injecting the sorbent into the tertiary air ports. The following operating variables were considered in optimizing for SO_2 capture:

1. Fuel composition
2. Sorbent composition
3. Injection location
4. Sorbent feed rate
5. Burner variables
6. Injection velocity

4.1 Sorbent Injection With Utah Coal

The potential of SO_2 reduction was evaluated for both Spreader #2 and Spreader #5 with Utah coal. Figure 4-1 summarizes the results from the sorbent injection tests with Utah coal. For the first configuration, shown as the open symbols, injection of the hydrated lime through the tertiary ports yielded the highest capture. Reduction of SO_2 was lowest with injection of Vicron through the tertiary ports and the addition of lime with the coal. Previous tests with bituminous coals have consistently shown that injection of lime with the coal is generally low when compared to other sorbent and injection combinations. This is probably due in part to the susceptibility of hydrated lime to deactivation in the high-temperature central regions of the flame. Another contributing factor considered is the interaction of the coal mineral matter with the sorbent particles. At elevated temperatures this interaction can diminish the available calcined sorbent surface area. Injection of Vicron through the pulverizer with this initial spreader configuration produced significantly better capture (37 percent at Ca/S = 2.0) than injection of the same material through the tertiary ports (29 percent at Ca/S = 2.0).

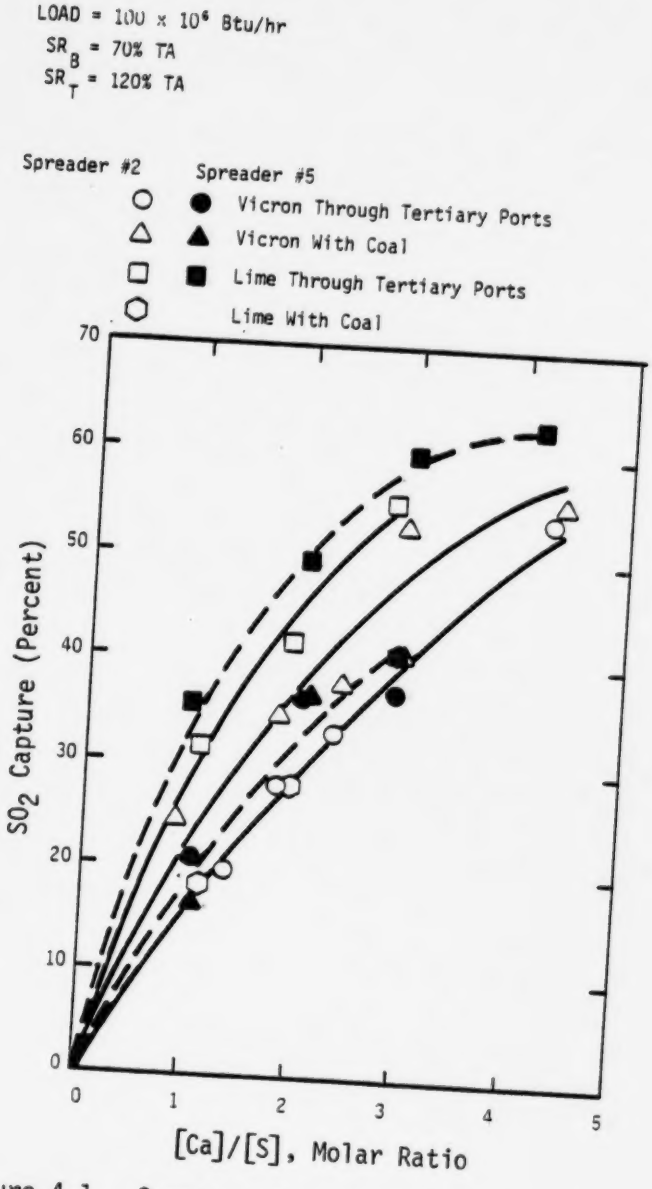


Figure 4-1. Summary of sorbent injection with Utah coal.

Sorbent injection tests with Spreader #5, also included in Figure 4-1, produced somewhat different results. The best capture for the sorbent/injection combinations evaluated was again achieved with the injection of lime through the tertiary ports. Sulfur capture by lime injected through the tertiaries was 49 percent at Ca/S = 2.0 for Spreader #5, higher than the capture achieved under comparable conditions with Spreader #2 (45 percent at Ca/S = 2.0). With the second spreader design, there was no significant difference between the captures achieved with Vicron injected through the tertiaries or with the coal. The average capture at Ca/S = 2.0 was 33 percent for Spreader #5 with Vicron addition in either location. This is lower than the capture with Vicron through the mill (37 percent), but higher than with Vicron through the tertiaries (29 percent) for the first configuration. The differences may be due to changes in mixing and recirculation patterns produced by the two speader designs. Burner performance, discussed in Section 3, was substantially different, with Spreader #5 producing a slightly shorter flame with corresponding higher NO_x emissions and improved efficiency.

Perturbations in burner variables were made while injecting Vicron through the tertiary ports to evaluate the potential of optimizing the RSC DMB to enhance SO_2 capture. The sensitivity of the RSC DMB performance to variations in burner parameters limited the range of the perturbations. The results of these burner adjustments on sulfur capture are compared to the capture achieved at the "NO_x-optimized" settings in Figure 4-2. None of the changes in burner settings improved capture. Only the retraction of the coal nozzle 2 inches yielded SO_2 reduction comparable to that achieved with the optimum settings. However, flame stability was diminished and a very short flame was produced as a result of the nozzle retraction. Burner performance for each adjustment is listed in Table 4-1. The results of these tests indicate that, for the RSC DMB, optimum performance for both NO_x and SO_2 reduction is achieved with the same burner conditions. Developments in the understanding of the LIMB process have not yet clearly identified the relative importance of "near-field" phenomena. The interaction of the sorbent jet with the flame, and the effect on sorbent calcination and activation, is for example poorly understood in large-scale systems. The large changes in SO_2 capture measured during these tests could therefore be related to the

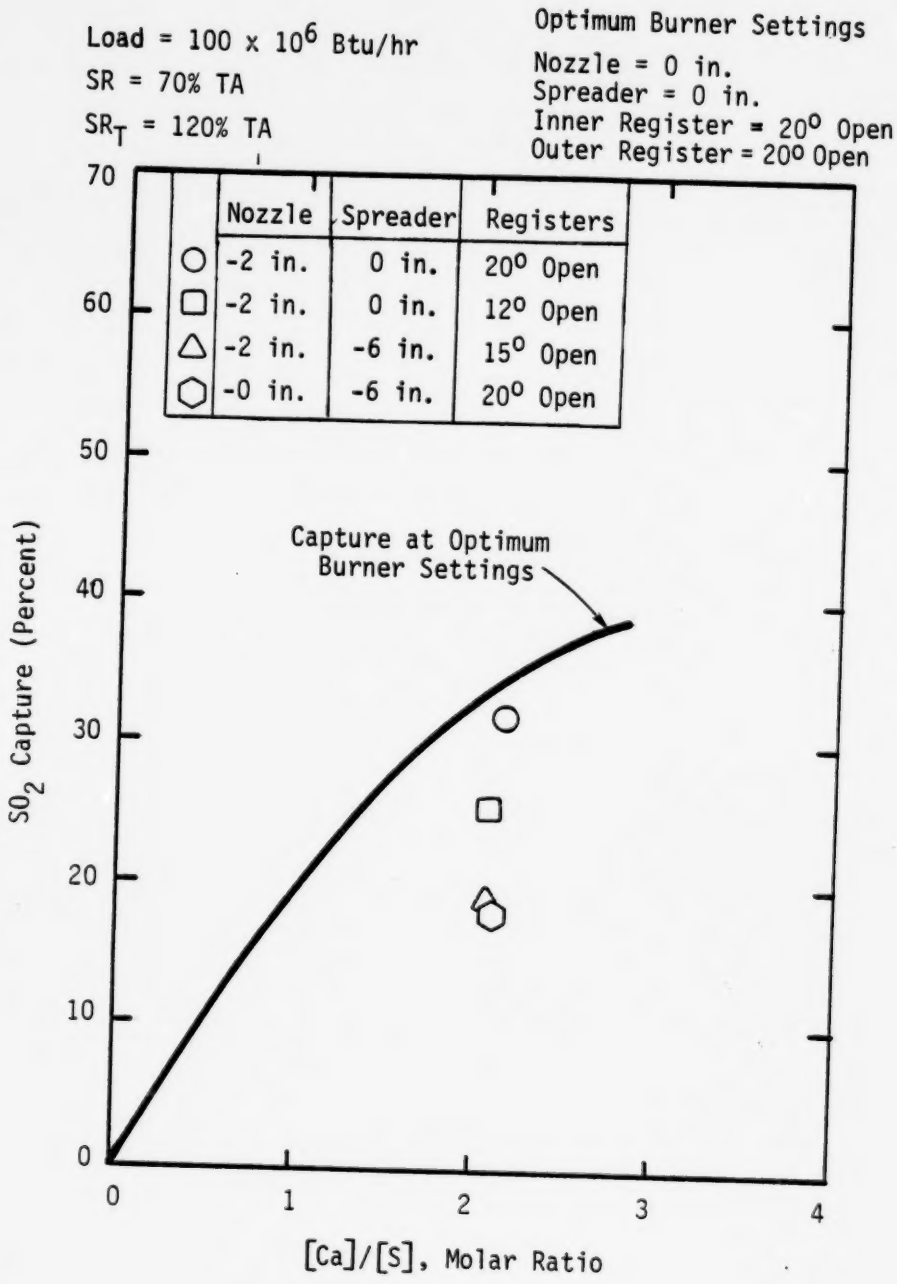


Figure 4-2. Effect of burner parameters on SO_2 capture with Vicron injected through tertiary air ports.

TABLE 4-1. BURNER PERFORMANCE DURING PERTURBATIONS FOR SO_2 OPTIMIZATION

Test No.	Nozzle (in.)	Spreader (in.)	Inner Register (° Open)	Outer Register (° Open)	Firing Rate (10^6 Btu/hr)	SR_B (% TA)	SR_T (% TA)	$\frac{[Ca]}{[S]}$	Capture (%)	NO_x (ppm)	CO (ppm)	Observations
19.2b	0	0	20	20	100.5	70	121	0	0	203	22	Optimum Condition; flame 20-ft. long.
19.4a	0	-6	20	20	98.7	69	120	2.11	18.1	171	22	Flame impingement on rear wall.
19.4b	-2	0	20	20	97.1	71	124	2.14	31.9	234	21	Unstable; short flame 16-17 ft. long.
19.4c	-2	0	15	15	99.2	69	120	2.10	19.0	217	22	Stable; flame 21-ft. long.
19.4d	-2	0	12	12	100.1	68	118	2.08	25.8	224	23	Flame impingement on rear wall.

observed flame instability that resulted from exceeding the narrow operating range of the RSC DMB.

Thermal environment is an important factor in the capture of sulfur species by sorbents. Residence time in the temperature regime necessary for sulfation predicates the degree of SO_2 reduction by the sorbent material. The effect of firing rate and its inherent effect on thermal environment was evaluated with sorbent injection at 60 percent of the RSC DMB capacity. The results are compared with full load tests (shown as solid lines) in Figure 4-3 for the Utah coal. The level of capture achieved at low load (27 percent at Ca/S = 2.0) with the Vicron limestone material, was lower than capture at full load (35 percent at Ca/S = 2.0) at Ca/S < 3. At Ca/S = 3, the capture at low load is comparable to that achieved at full load. The feeding rate necessary for Ca/S = 1 at low load was near the lower limit of the sorbent feeder operating range with the result that the feed rate was probably intermittent and actually lower than indicated. This may account for the very low capture at Ca/S = 1. At Ca/S = 2.0, there was no significant difference between injection locations for Vicron as in the case of the full load tests. The hydrated lime again achieved the highest capture (48 percent at Ca/S= 2.0). At Ca/S > 1.6, the effectiveness of the lime decreases at low load. Gas temperatures measured at the exit of the LWS with an aspirated thermocouple were in the range of 1650°F at low lod(60×10^6 Btu/hr) while at full load (100×10^6 Btu/hr) the exit temperature was 1850°F. The ideal temperature window for the most favorable sulfation rates has been identified as 2200-1500°F. Because of the nature of the LWS furnace, a reduction in load increases mean residence time but also reduces the mean furnace temperature. The result is that the time available in the sulfation temperature window is relatively insensitive to load, and little effect of firing rate on sulfur capture would be expected.

4.2 Sorbent Injection With High Sulfur Fuels

Coal from Indiana has been used in the various test furnaces at EER as the base fuel for LIMB studies because of its relatively high sulfur content. Figure 4-4 summarizes the test results of sorbent injection with the RSC DMB

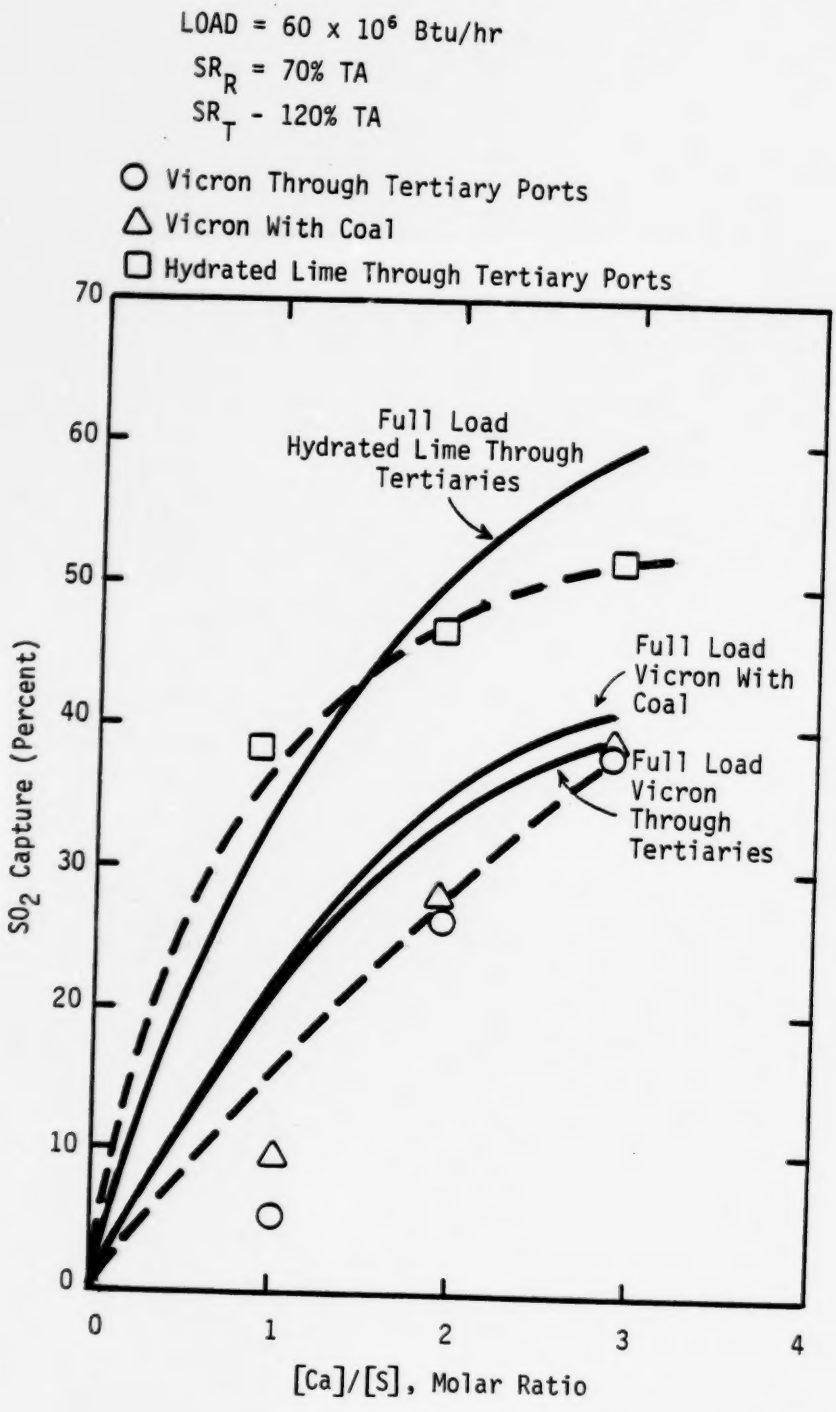


Figure 4-3. Effect of load on SO_2 capture with Utah coal.

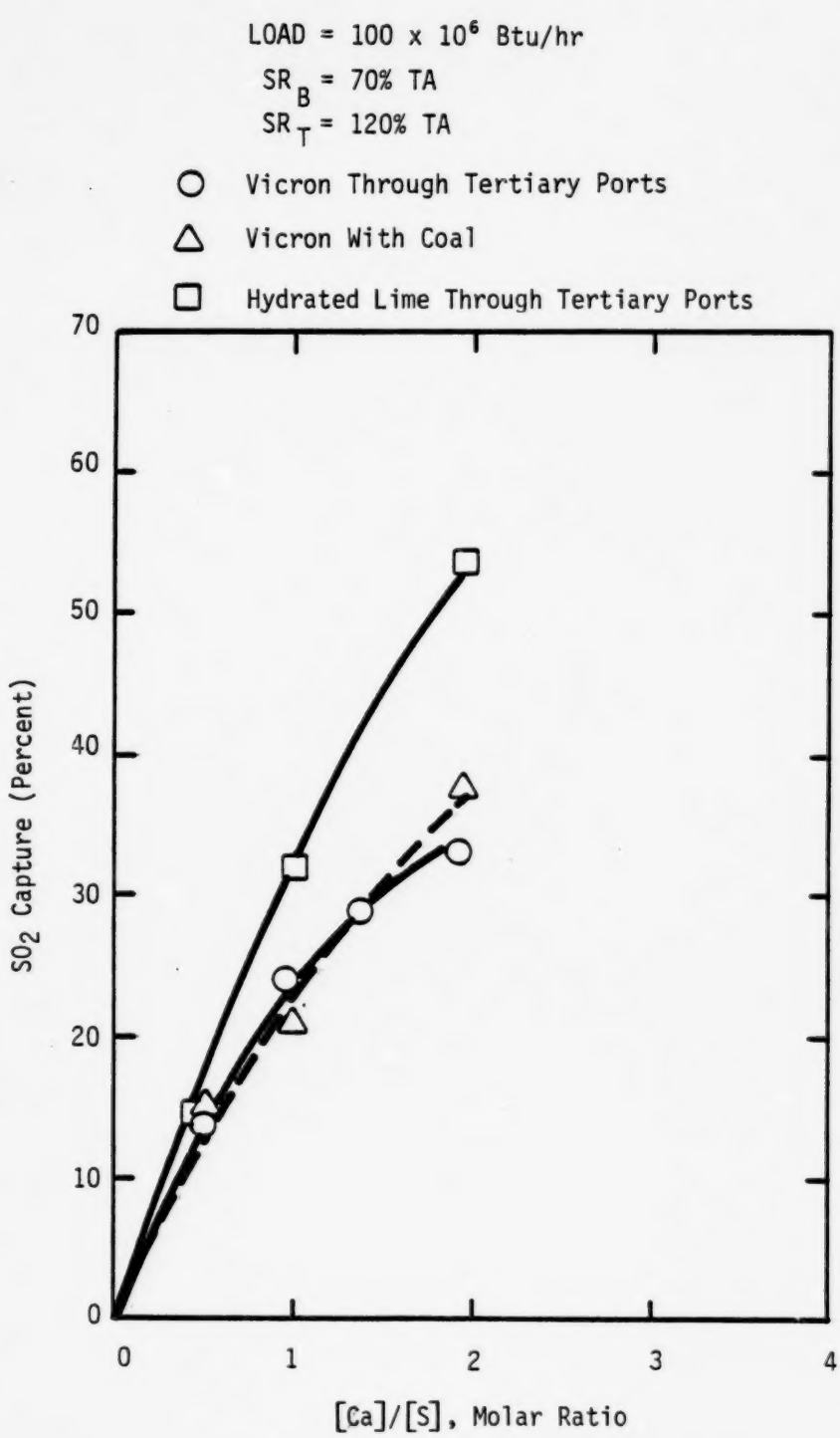


Figure 4-4. Summary of sorbent injection with Indiana coal.

firing Indiana coal. As with the Utah coal, the injection of hydrated lime yielded the highest levels of SO_2 capture (54 percent at Ca/S = 2.0). There was no measurable effect of injection location on capture with Vicron as the sorbent. SO_2 capture with Vicron was approximately 35 percent at Ca/S = 2.0.

The Illinois coal tested represents a fuel used at an operating RSC boiler, CILCO Duck Creek Unit 1, that will be used to relate the LWS test results with field units. The sorbent feed system capacity was not sufficient to supply sorbent material to achieve calcium-to-sulfur molar ratios over 1.6 because of the high sulfur content (3.97 percent) of the Illinois coal. Figure 4-5 presents the sulfur capture data over the limited range that could be achieved. The hydrated lime was again the most effective sorbent. Injection of Vicron through the tertiary ports achieved slightly better capture than injection with the coal, although there was no difference at the highest Ca/S ratio that could be reached (1.6). The differences between the two injection locations may not be significant. In a brief low-load test at 65 x 10^6 Btu/hr, injection of limestone through the tertiary ports achieved about 31 percent capture at Ca/S = 1.55. This is comparable to the capture at full load (28 percent at Ca/S = 1.6).

The trends for all three fuels were similar, with the best performance in terms of sulfur capture achieved by injecting lime through the tertiary air ports, and with little difference in the effectiveness of injection locations with Vicron. Figure 4-6 presents the previously discussed data for Ca/s <4.0 on the basis of sorbent/injection location combinations to illustrate the effect of fuel composition. Intuitively, an effect of composition (sulfur content, in particular) would be anticipated. The sulfation reaction would be thought to be driven in part by the concentration of sulfur species. The SO_2 capture data presented shows no discernible effect of coal composition for the RSC DMB system.

4.3 Aerodynamics of Sorbent Injection

Based on general interest, a brief series of tests were conducted with variable sorbent injection velocity. This was achieved by varying the amount

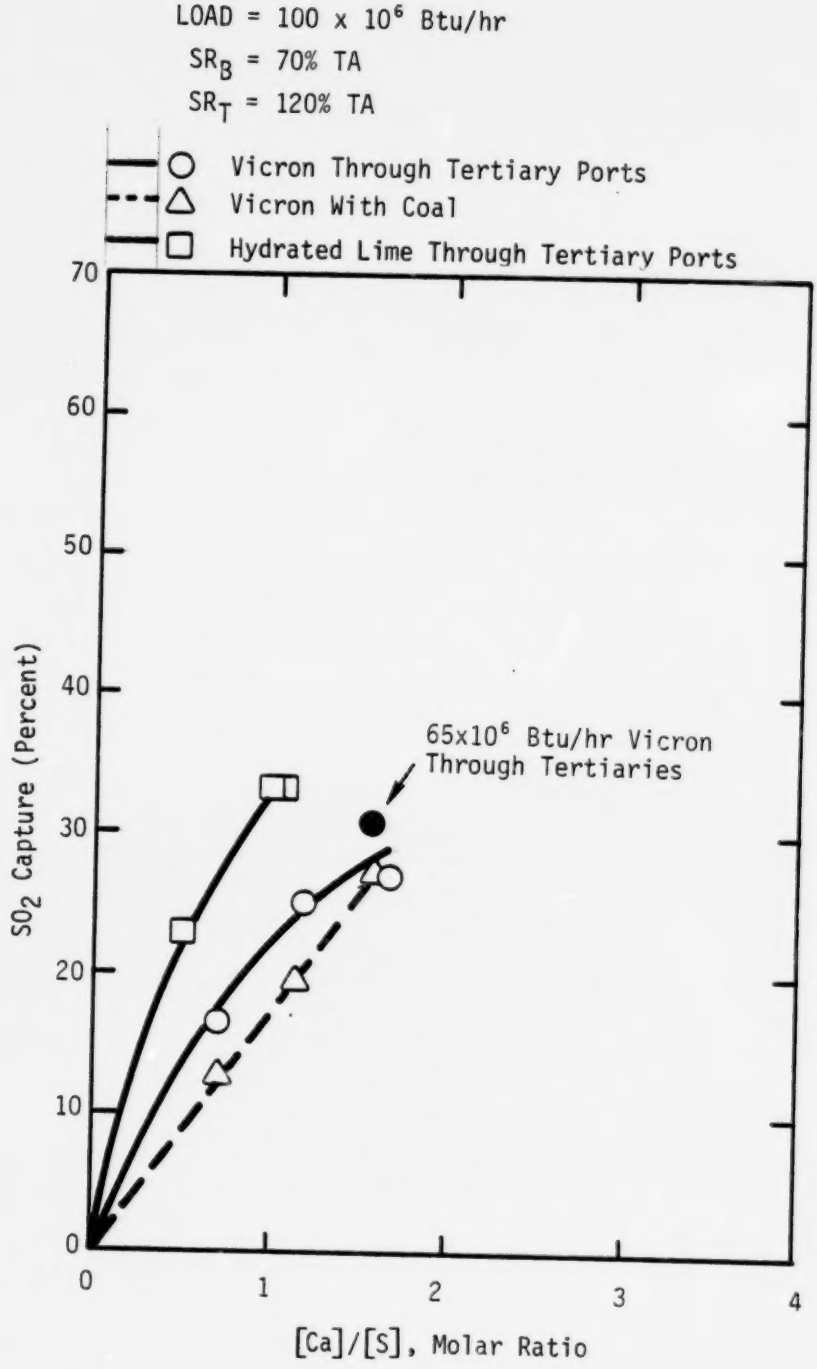


Figure 4-5. Summary of sorbent injection with Illinois coal.

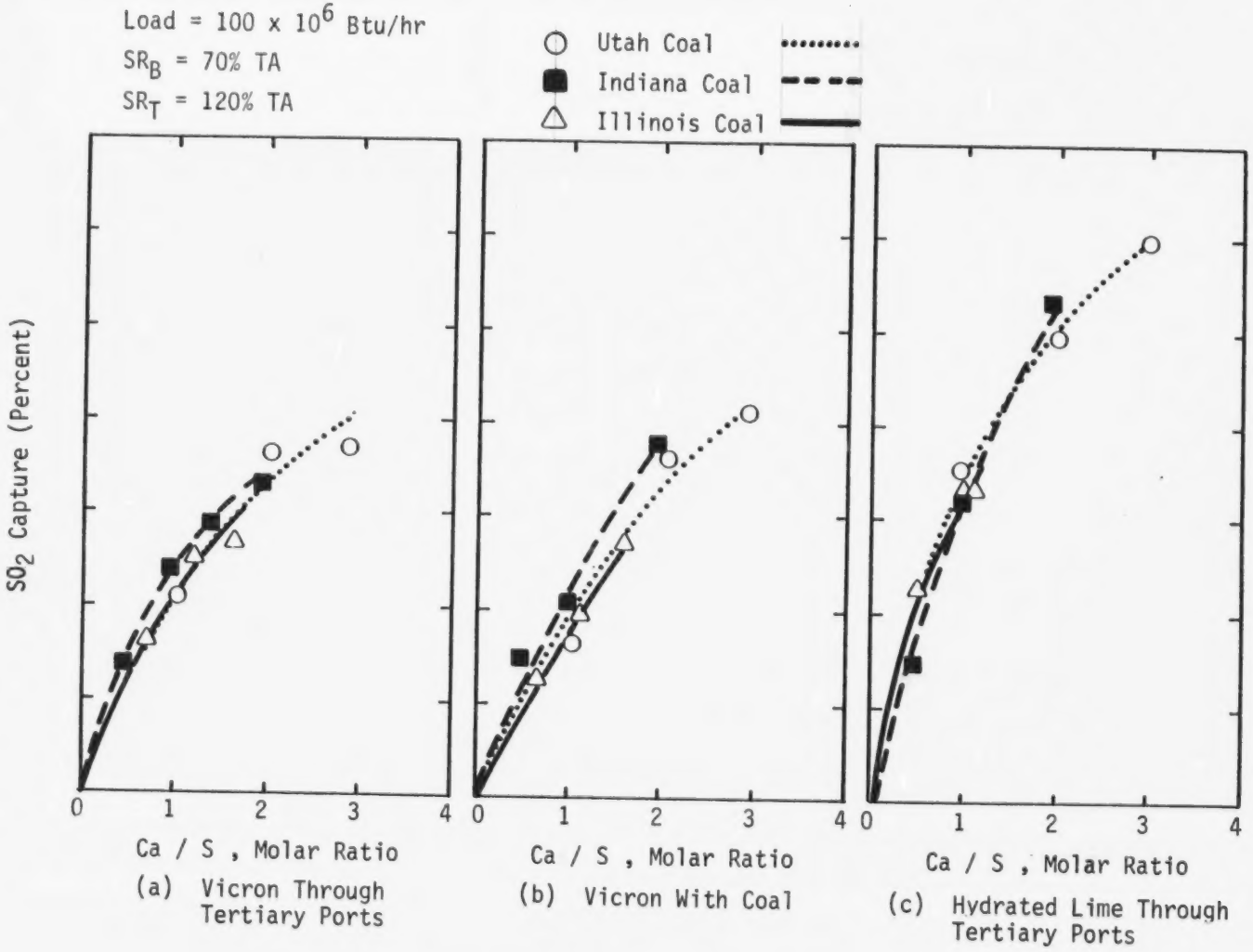


Figure 4-6. Effect of coal composition on SO_2 capture.

of transport air used in the sorbent injection pipes. For these tests where sorbent was injected through the tertiary air ports, the actual sorbent injection pipes were concentric on the axis of the tertiary air port. The sorbent was transported with an air flow which was independent of the tertiary air flow. The first series of tests utilized the optimum RSC DMB configuration with the high velocity, 8-in. diameter tertiary air ports. The sorbent injection velocity was considered relative to the tertiary velocity, with a dimensionless ratio, λ, defined as:

$$\lambda = \frac{v_{tertiary}}{v_{injection}}$$

Figure 4-7(a) shows the results of the preliminary tests. For constant tertiary velocity, decreasing the sorbent injection velocity resulted in a reduction in SO_2 capture. High sorbent injection velocities were necessary to achieve $\lambda < 1$ with the small tertiary ports. To evaluate the low range of this relative velocity parameter, the small tertiary inserts were removed leaving 12-in. diameter tertiary ports. Because of flame length considerations, the RSC DMB was operated at a burner zone stoichiometry of only 80 percent TA rather than at its design point of 70 percent TA. These conditions yielded tertiary velocities of about 72 ft/sec. The results from these tests are presented in Figure 4-7(b). For this particular arrangement, a reduction in sorbent injection velocity resulted in a significant decrease in SO_2 capture.

During the sorbent injection tests preceding this investigation of sorbent injection velocity, constant sorbent air flow was maintained to the extent possible. High sorbent feed rates generally resulted in increased resistance to the air flow, thus some variation in transport flow and velocity was experienced. Table 4-2 summarizes the sorbent velocity ratios for these tests. The majority of the full load tests with Spreader #5 were conducted with the injection velocity matching the tertiary velocity $\lambda = 1$. The low load tests with Utah coal used similar sorbent air flow and velocity as in the full-load tests to ensure adequate air flow for transporting the sorbent material; however, tertiary velocities were lower because of the

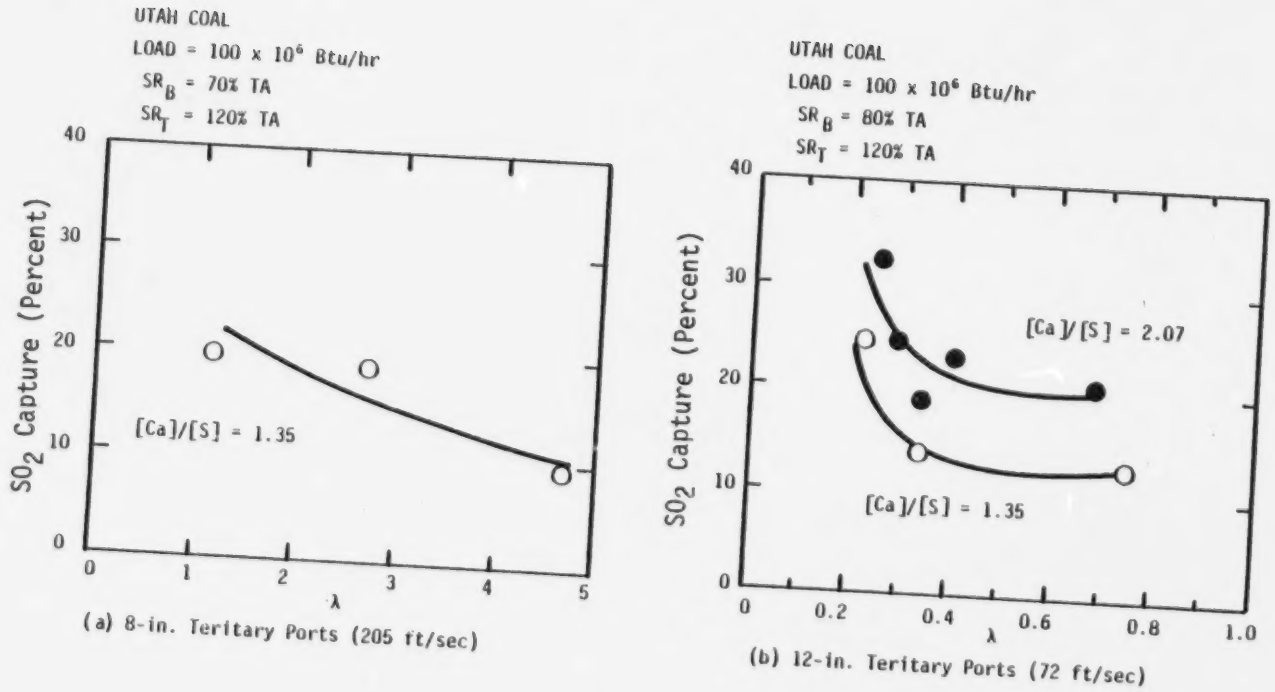


Figure 4-7. Effect of injection velocity on SO_2 capture with Vicron.

TABLE 4-2. SORBENT VELOCITY RATIOS USED IN RILEY STOKER CORPORATION SORBENT INJECTION TESTS

Coal	Firing Rate (10^6 Btu/hr)	Spreader Design	$\lambda = \frac{v\,\text{Tertiary}}{v\,\text{Injection}}$	
			Mean	Std. Dev.
Utah	100	#2	1.5	0.2
Utah	100	#5	1.1	0.2
Utah	60	#5	0.7	0.2
Indiana	100	#5	1.0	0.3
Illinois	100	#5	0.8	0.2

decreased air flow required to maintain design point excess air and burner zone stoichiometry. The result of this combination was a velocity ratio less than unity. Although there were differences in sorbent velocities and for the various test conditions, the data in Figure 4-7 imply that there is little effect on SO_2 capture by λ in the range of 0.7 to 1.5.

5.0 CHARACTERIZATION OF THE RILEY STOKER CORPORATION DMB

Manual measurements were made to obtain data characterizing the performance of the RSC DMB with and without sorbent materials. The detailed measurements included:

1. Temperature profile of the flame.
2. Mass loading of the fly ash particles.
3. Size distribution of the fly ash particles.
4. Analysis of the chemical composition of the fly ash.
5. Slagging and fouling characteristics.
6. SO_3 concentration in the flue gas.

Measurement of the internal flame temperature profile provides information regarding recirculation patterns and thermal environment to which sorbent materials are exposed. The physical and chemical properties of particulate matter yield information on combustion efficiency, sorbent utilization, potential impact on particle control efficiency, and slagging and fouling characteristics with and without sorbent.

5.1 Internal Flame Temperature Profile

The flame temperature profile of the RSC DMB was measured utilizing a water-cooled suction pyrometer. The suction pyrometer was inserted through ports on the north side of the LWS located on the burner centerline, yielding the temperature profile in Figure 5-1. Traverses through each port were made in one-foot increments, but measurements at the centerline of the furnace could not be made because of physical restrictions to the movement of the probe. The peak temperature measured in the traverse was 2320°F, about 100°-200°F lower than anticipated maximum flame temperatures. Higher temperatures could possibly have been measured at the centerline.

An illustration of the temperature traverses is presented in Figure 5-2. The high tertiary velocity appears to push the flame out along the line of

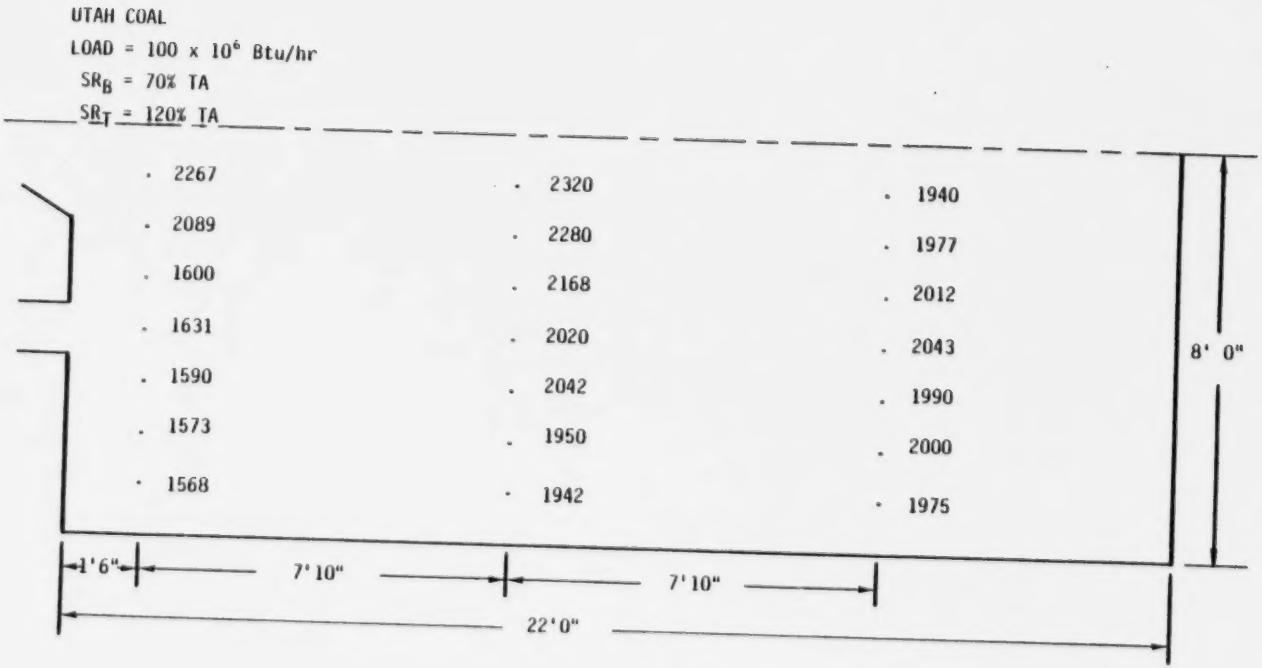


Figure 5-1. In-flame temperature profile of horizontal plane through Riley Stoker Corporation centerline (all temperatures in ^{o}F).

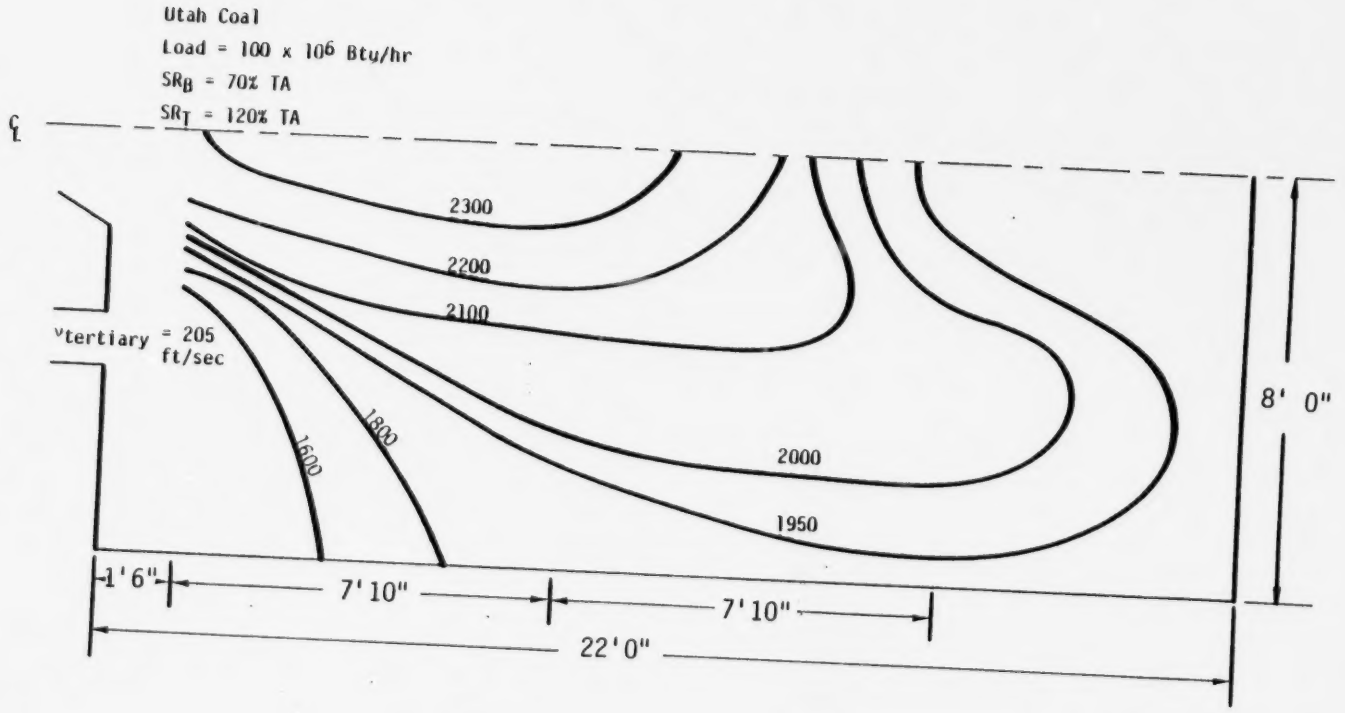


Figure 5-2. Estimated isotherm contour profile of horizontal plane through Riley Stoker Distributed Mixing Burner centerline.

the tertiary ports. This produces an extended region of temperatures in the range of 1950°-2000°F in line with the path of sorbent particles injected through the tertiary air ports.

5.2 Fly Ash Characteristics

The physical and chemical properties of selected fly ash samples are listed in Table 5-1. The samples selected allow comparison between staged and unstaged conditions, fuel composition, and the presence or absence of sorbent materials. The analysis conducted of the samples included measurements of particle loading, size distribution, elemental analysis, and ash melting characteristics.

5.2.1 Particle Mass Loading

Measurement of particle loading was done utilizing EPA Reference Method 5, traversing across the sample duct of the LWS to obtain a representative isokinetic sample. Only two conditions were considered because of the time-consuming nature of the measurement: full load, staged operation with Utah coal with and without sorbent injection. The test numbers 22.3 and 23.3 conditions were as nearly identical as possible with the only difference being the injection of Vicron through the tertiary ports at Ca/S = 2 during test 23.3. The mass loading measured for Test 22.3 was 475.4 lb/hr of ash or a concentration of 3.022 gr/scf (corrected to 3 percent O_2). The anticipated particle loading based on coal composition was 856 lb/hr which indicates a retention in the furnace of 44 percent of the ash. For the case of sorbent injection, Test 23.3, the loading was 747.4 lb/hr of ash or a concentration of 4.702 gr/scf (corrected to 3 percent O_2). The additional noncombustible material in the form of Vicron increased the theoretical loading to 1239 lb/hr. This indicates that the furnace system retained 40 percent of the ash and sorbent. The indicated retention by the furnace was comparable for both test conditions. This implies that the measured increase in particle loading may be used as an indication that the additional solid material will be distributed relatively evenly among fouling material, bottom ash, and fly ash

TABLE 5-1. SUMMARY OF PHYSICAL AND CHEMICAL PROPERTIES OF SELECTED FLY ASH SAMPLES

Test Condition	Test No.	18.1	22.3A	23.3D	20.12	21.4	14.2	14.8	16.4	17.5
	Coal	Utah	Utah	Utah	Utah	Utah	Ind.	Ind.	Ill.	Ill.
	Load (10^6 Bt /hr)	98.8	102.1	97.4	101.2	61.7	99.3	103.0	102.7	97.8
	SRB (% TA)	114	69	71	70	69	72	71	70	70
	SRT (% TA)	121	119	122	121	117	121	120	122	121
	Sorbent	---	---	Vicron	Vicron	Vicron	---	Vicron	---	Vicron
	Location	---	---	Terts	Mill	Terts	---	Terts	---	Terts
	Ca/S	---	---	2.13	2.05	1.94	---	1.38	---	1.65
	Capture (%)	---	---	26.9	36.4	26.4	---	28.9	---	26.9
Ultimate (Dry)	C (%)	7.97	10.02	7.97	6.99	*	8.01	3.70	6.19	2.84
	H (%)	0.50	0.31	0.11	0.18	*	0.14	0.09	0.10	0.20
	N (%)	0.08	0.29	0.11	0.16	*	0.04	0.04	0.03	0.07
	S (%)	2.99	0.66	1.29	2.50	3.15	2.06	2.07	2.79	4.82
	Ash (%)	82.18	88.07	90.52	89.81	*	90.66	94.96	92.72	95.28
	O (%)	6.28	0.65	0	0.36	*	0	0	0	0
Elemental Ash	SiO_2 (%)	49.39	64.14	50.47	45.94	39.59	46.51	36.59	44.28	29.93
	Al_2O_3 (%)	17.78	19.79	15.33	16.28	14.93	22.11	20.03	19.44	13.24
	TiO_2 (%)	0.67	0.74	0.46	0.62	0.72	0.57	0.47	0.31	0.27
	Fe_2O_3 (%)	10.17	4.70	3.28	4.19	3.12	18.98	19.03	15.93	10.71
	CaO (%)	13.05	7.35	20.80	22.46	29.16	5.64	18.17	10.40	30.98
	MgO (%)	0.15	0.26	0.77	1.06	1.46	0.87	0.21	1.98	1.26
	Na_2O (%)	1.06	1.15	0.89	1.14	0.91	0.77	0.30	0.85	0.80
	K_2O (%)	1.00	0.95	0.85	0.90	0.78	0.86	0.49	1.30	1.08
	P_2O_5 (%)	0.33	0.41	0.31	0.42	0.35	0.35	0.25	0.31	0.31
	SO_3 (%)	7.35	1.85	6.34	6.65	9.11	3.79	5.35	5.89	13.10
Ash Fusion Temp Oxid.	IDT (^oF)	2180	2310	2150	2120	2160	2310	2380	2290	2140
	ST (^oF)	2310	2405	2200	2190	2175	2540	2450	2420	2175
	HT (^oF)	2380	2570	2250	2260	2185	2570	2475	2440	2180
	FT (^oF)	2410	>2700	2430	2380	2210	2600	2525	2510	2230
Ash Fusion Temp Red	IDT (^oF)	2065	2305	2095	2010	2040	2140	2130	2140	2135
	ST (^oF)	2190	2400	2175	2150	2150	2260	2275	2210	2150
	HT (^oF)	2295	2540	2210	2180	2155	2415	2310	2285	2160
	FT (^oF)	2375	2640	2385	2260	2180	2520	2395	2385	2185
	L.O.I.@ 500^oC (%)	4.95	9.05	6.87	6.41	15.14	9.88	4.15	4.04	2.04
	L.O.I.@ 750^oC (%)	6.37	10.12	9.33	8.99	18.22	10.11	4.85	8.07	3.80
	L.O.I.@ 1000^oC (%)	6.53	10.63	9.81	9.39	19.00	11.68	5.11	8.63	4.11
	Mass Median DIA (μm)	16.8	29.5	19.0	10.7	---	11.2	16.0	12.3	14.8
	Particle Loading (lb/hr)	---	475.4	747.4	---	---	---	---	---	---
	Concent.@ 3% O_2 (gr/scf)	---	3.022	4.702	---	---	---	---	---	---

*Insufficient sample for analysis.

5.2.2 Particle Size Distribution

Particle size distribution was determined by an outside laboratory using X-ray sedimentation. Results of the analyses for tests with Utah, Indiana, and Illinois coals are presented graphically in Figures 5-3, 5-4, and 5-5, respectively. Four test conditions with Utah coal are compared in Figure 5-3. The mass median diameter varied substantially. Mass median particle size was smaller for unstaged flames (16.8 μm) than staged conditions (29.5 μm). When limestone was injected, the median particle size decreased to 19.0 μm for tertiary injection and 10.7 μm for mill addition. Laboratory tests have shown that limestone materials can exhibit severe fragmentation, reducing mean sorbent size by a factor of two at in-flame temperatures. This may account in part for the bias toward smaller particles for the test of Vicron injected with the coal. For the higher sulfur coals, injection of Vicron through the tertiaries resulted in an increase in particle size, which may or may not be significant. Further, the mass median particle diameters with no sorbent are similar for the Indiana (11.2 μm) and Illinois (12.3 μm) as are the diameters with sorbent injection for Indiana (16.0 μm) and Illinois (14.8 μm) coals.

5.2.3 Laboratory Analysis of Ash Composition

Table 5-1 summarizes the analyses performed on the ash of selected test conditions. The tests without sorbent for all the coals show relatively low carbon content, 6.19-10.02 percent. This is an indication of efficient combustion, resulting in carbon utilization under the staged conditions listed of 98.3 percent for Utah coal, 98.8 percent for Indiana coal, and 99.0 percent for Illinois coal.

Comparison of the elemental analyses of the ash mineral matter show no large variations in composition for different conditions for each coal except for the weight percent of SiO_2, CaO, and SO_3. The CaO weight percent content rises for conditions of sorbent injection, as expected. The SO_3 also rises with sorbent material. The decrease in SiO_2 is largely due to the increase in CaO from the injected sorbent diluting its concentration. Concentrations

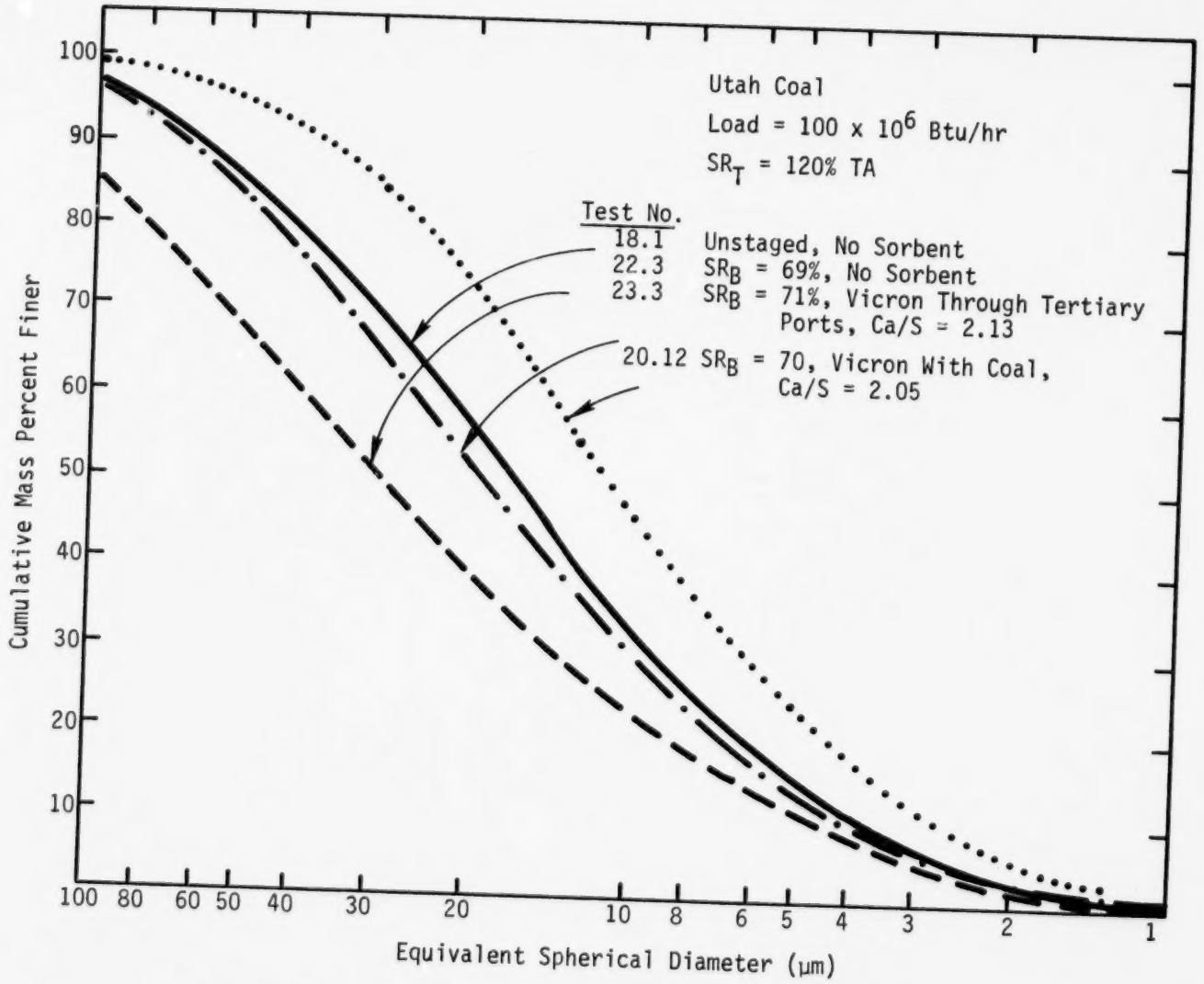


Figure 5-3. Particle size distributions for Utah coal.

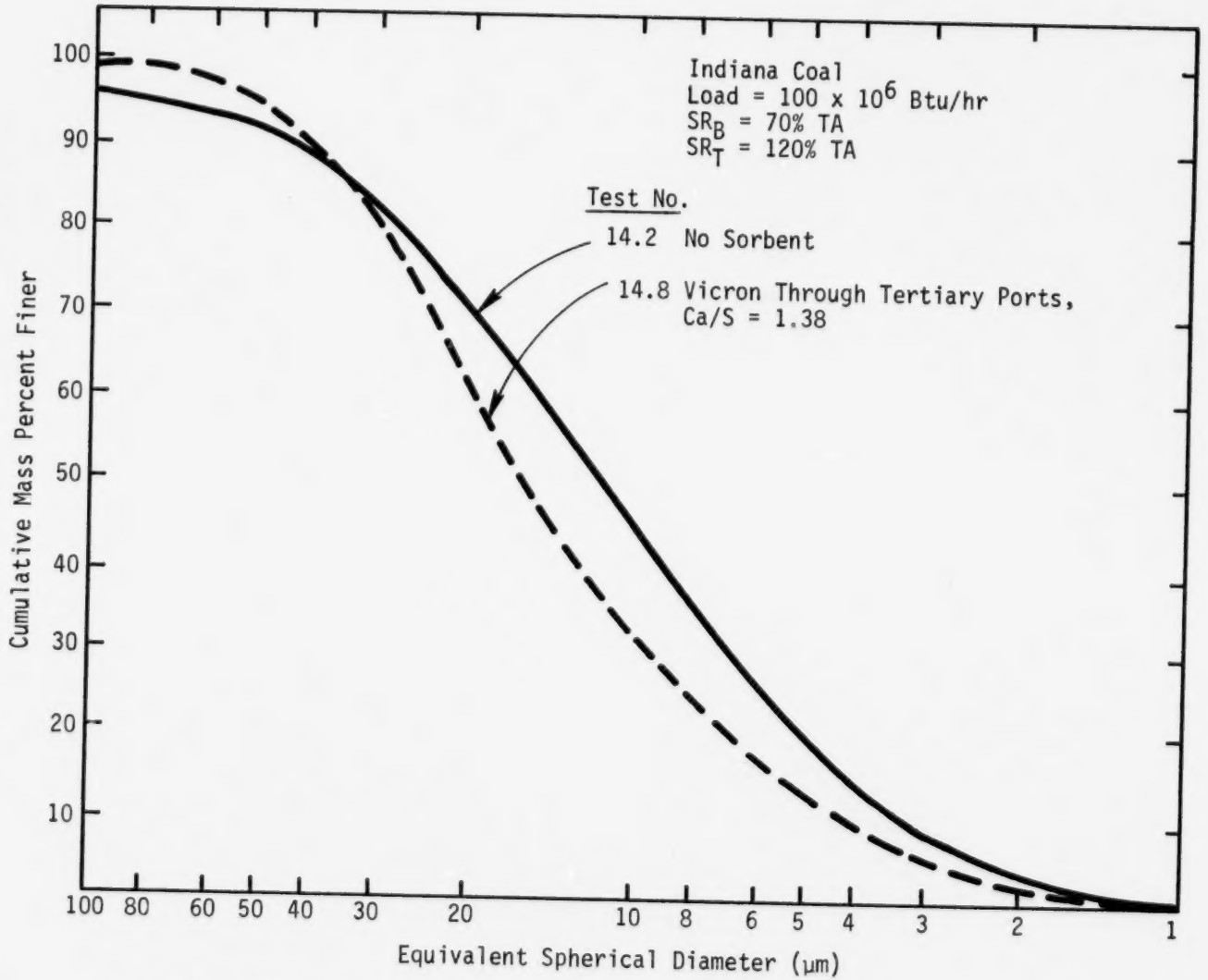


Figure 5-4. Particle size distributions for Indiana coal.

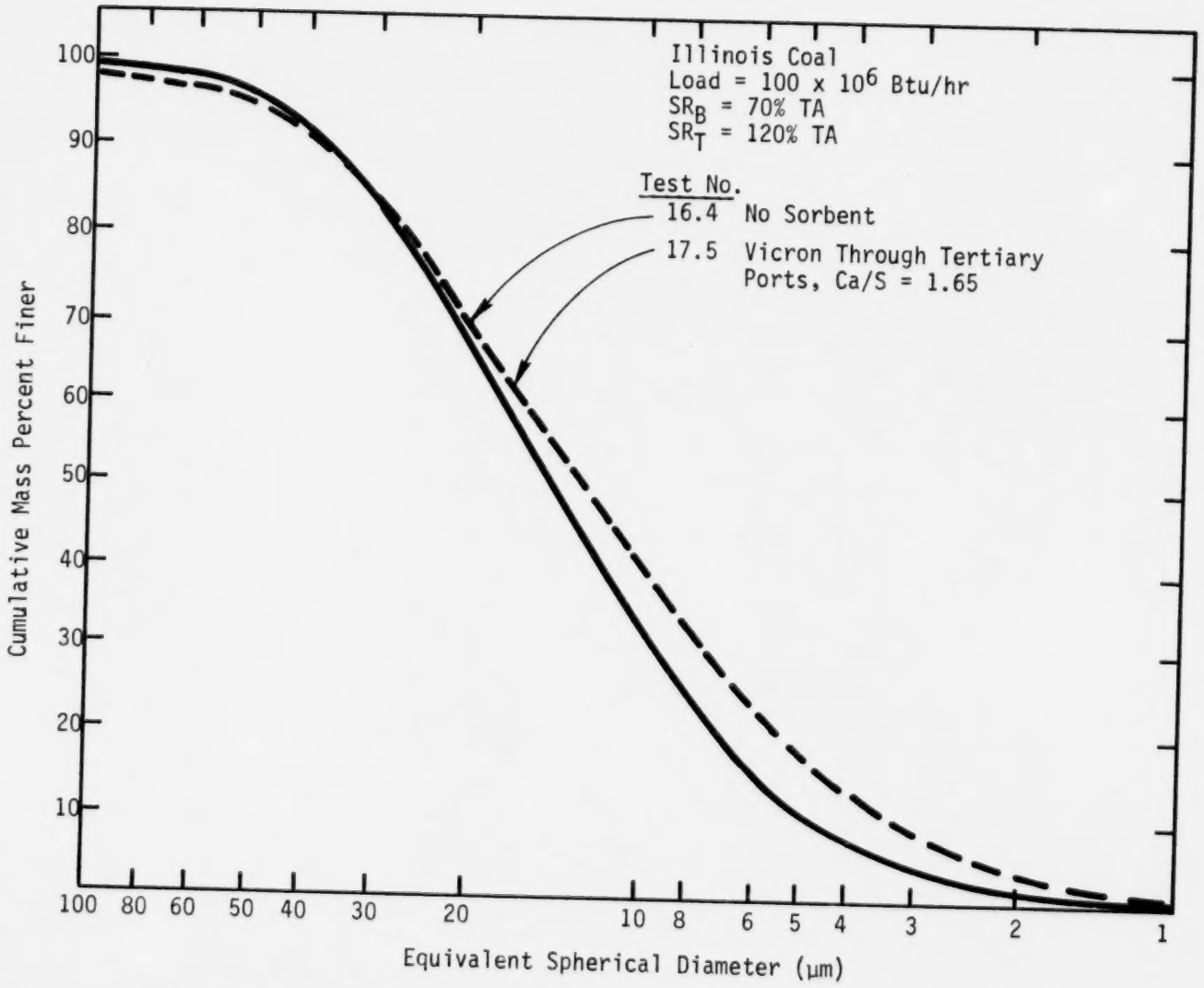


Figure 5-5. Particle size distributions for Illinois coal.

of CaO from the coal analyses listed in Table 2-2 predict substantially lower levels of CaO than measured from fly ash samples collected for baseline conditions of each coal during the sorbent injection studies. This implies that some of the sorbent material may have been retained in the LWS and then reentrained during baseline conditions. The ash sample of test #18.1, Utah coal unstaged without sorbent injection, was obtained following tests of Illinois coal with sorbent injection. The analysis of sample 18.1 indicates significant carryover resulting in a sample which is probably not representative of the test conditions. Calcium utilization efficiency can be calculated using the CaO and S content of the ash as well as from the gas phase species alone. The two methods are compared for selected conditions in Table 5-2. The agreement in the two independent methods is generally good.

Ash composition affects the melting characteristics and the tendency of the ash to slag or foul boiler surfaces. Included in Table 5-1 are ash fusion temperatures under oxidizing and reducing conditions. Reducing conditions are usually compared, since those conditions represent the worst case with lower melting temperatures. For Utah coal under staged conditions, the addition of sorbents greatly reduces the temperatures required to melt the ash. The initial deformation temperature (IDT) decreased from 2305°F with no sorbent, to 2010°F when Vicron was injected with the coal at Ca/S =2.05. The effect on the ash-melting temperatures is not as clear for the two higher sulfur coals. There is actually no significant difference in the melting points of the ash with or without sorbent until the hemispherical temperature (HT) is reached, where the sorbent added ash melts at temperatures more than 100° lower. These reduced ash fusion temperatures could greatly affect boiler operation with increased slagging and fouling.

5.3 Slagging and Fouling Characteristics

Deposition of coal particulate matter on boiler surfaces in both the radiant section and convective pass was evaluated during tests of the RSC DMB. Three refractory-faced, water-cooled panels were installed in the LWS along the burner centerline on the south and rear walls to provide deposition surfaces in the radiant zone. An array of six stainless steel tubes, 2 tubes

TABLE 5-2. COMPARISON OF SORBENT UTILIZATION EFFICIENCIES

Test No.	23.3	20.12	20.8	14.8	15.10	14.12
Coal	Utah	Utah	Utah	Indiana	Indiana	Indiana
Load (10^6 Btu/hr	102.1	101.2	101.2	103.0	101.7	101.9
SR_B (% TA)	69	70	69	71	69	72
SR_T (% TA)	119	121	120	120	118	124
Sorbent	Vicron	Vicron	Lime	Vicron	Vicron	Lime
Location	Terts	Mill	Terts	Terts	Mill	Terts
Ca/S Molar Ratio	2.13	2.05	2.0	1.38	1.95	1.97
Capture (%)	26.9	36.4	49.4	28.9	37.8	53.5
Ash S (%)	1.29	2.73	2.65	2.07	3.32	3.6
Ash CaO (%)	20.8	22.46	20.7	18.17	24.10	24.4
Gas Phase[1] Utilization (%)	12.6	17.8	24.7	20.9	19.4	27.2
Solid Phase[2] Utilization (%)	10.9	21.3	22.4	19.9	24.1	25.8

[1] Gas Phase Utilization = $\frac{\text{Gas Phase } SO_2 \text{ Capture (\%)}}{\text{Ca/S}}$

[2] Solid Phase Utilization = $\frac{\text{Ash S \%}}{\text{Ash CaO \%}} \times \frac{56}{32} \times 100$

wide x 3 tubes deep, cooled using a radiative heat sink, was installed above the nose of the furnace to simulate tubes in the convective pass. The slagging panels were equipped with thermocouples and a metered water flow so that heat flux through the panels could be monitored. The fouling probe assembly above the LWS nose was equipped with thermocouples and a developmental load cell system intended to measure the rate of ash deposition on the tubes.

The deposits on the slagging panels were generally the same for each of the coals under similar operating conditions. The mass deposited tended to vary daily, but this appeared to be caused by the sloughing off of collected material either during cooling or during removal of the panels for inspection. The collected mass during sorbent injection tests was comparable to that collected with no sorbent injection. Two distinct layers formed on the panels. The layer adjacent to the surface of the panels was of a dry, powdery consistency. The outer layer, exposed to higher temperatures, was sintered and consisted of densely packed, 1/4-inch diameter nuggets. These nuggets were friable and there was no evidence of molten slag.

A typical example of panel surface temperature and heat flux changes during testing is shown in Figure 5-6. There is no measurable difference in the temperature or heat flux variations during tests with and without sorbent injection. The slagging panel surface temperature increases initially, reaching maximum temperature 2 to 3 hours after coal firing was begun. The surface temperature then decreases monotonically as the ash layer increases. The calculated heat flux remains relatively constant for the duration of the test. The thermal inertia of the refractory face probably masks the discrete changes in the amount of heat absorbed by the cooling water resulting from relatively small increases in the deposited ash layer.

The deposits on the fouling probes in the exit of the LWS consisted of powdery ash for each of the three coals; however, the pattern of distribution was substantially different. The deposits for the two eastern coals, Indiana and Illinois, collected on the front of the tubes, while for the Utah coal the deposits were on the back side. One possible explanation could be the

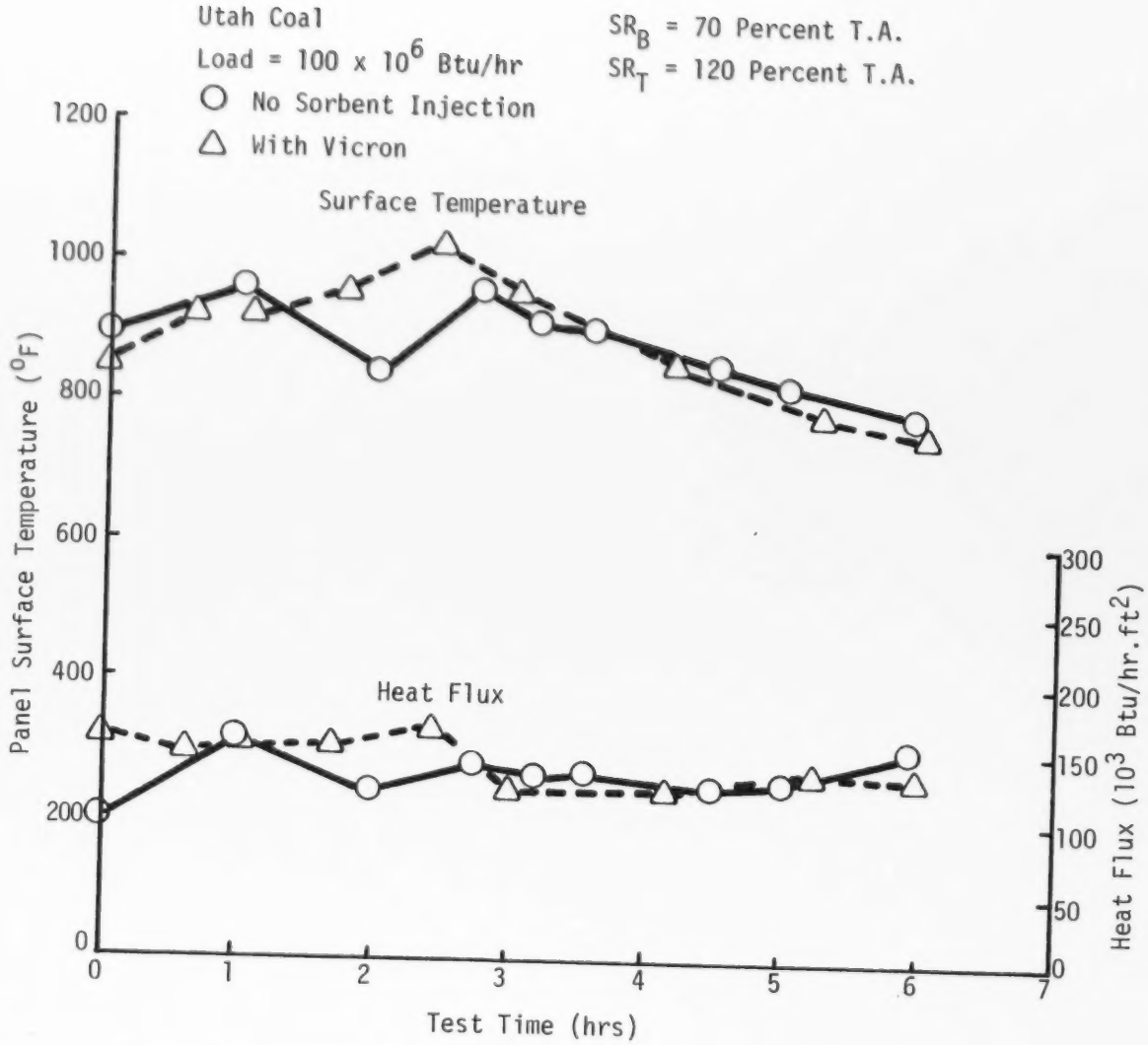


Figure 5-6. Typical thermal history of rear wall slagging panel.

different densities of the ashes. Both the Indiana and Illinois coals have high iron contents, 27.85 and 18.41 percent in ASTM coal ash. The reddish-brown color of the deposits from these two coals also implies high iron content. The deposits of the Utah ash on the fouling probes were almost white in color, free of iron. Iron oxide has a substantially higher density, 5.24 gm/ml, than the ash from Utah coal, about 2.5 gm/ml. The heavier particles would tend to impact the tubes, not being able to follow the streamlines around the tubes, and collect on the front. The lighter ash particles from the Utah coal would tend to be caught in the recirculating wake of the tubes and thus collect on the back side.

Past researchers have developed indices based on coal ash composition and physical properties. Table 5-3 lists a few of the many available correlations applied to selected RSC DMB test conditions. Similar test conditions are considered for each coal: full load, staged operation with approximately 20 percent excess air. Both tertiary injection of limestone at Ca/S 2 and no sorbent injection are compared. In general, the indices imply that the addition of sorbent material would tend to increase the slagging potential of the ash. Ash viscosity temperatures indicate temperatures at which slag flow properties change from Bingham plastic to Newtonian (T_{cv}) and at which the slag will flow on a vertical wall with a viscosity of 250 poise (T_{250}). Dolomite ratio and Base/Acid ratio are indices of the basic constituents of the ash and have been used to predict ash viscosity properties. In general, an increase in Dolomite ratio increases the slag viscosity.

Ash type is characterized as lignitic when the Fe_2O_3 concentration is less than MgO + CaO and as bituminous ashes when the Fe_2O_3 content is greater than MgO + CaO. These designations are used to separate correlations for eastern (bituminous) and western (lignite) coals. Fouling indices included in Table 5-3 are based primarily on ash type and sodium (Na_2O) content. Although the RF index applies to eastern coals, the addition of the limestone for test 17.5 changes the ash type to lignite from bituminous. This change probably makes the RF index not applicable. RF indices between 0.2 and 0.5 are classified as medium fouling ashes, while ashes between 0.5 and 1.0 are high-fouling. Two different indices for slagging potential (RS) are

TABLE 5-3. INDICES OF SLAGGING AND FOULING POTENTIAL FOR SELECTED TEST CONDITIONS

Test No.	22.3A	23.3D	14.2	14.8	16.4	17.5
Coal	Utah	Utah	Ind.	Ind.	Ill.	Ill.
Sorbent	---	Vicron	---	Vicron	---	Vicron
Location	---	Terts.	---	Terts.	---	Terts.
Ca/S	---	2.13	---	1.38	---	1.65
Measured Ash Fusion Temperature:						
IDT (°F, Red.)	2305	2095	2140	2130	2140	2135
ST (°F, Red.)	2400	2175	2260	2275	2210	2150
HT (°F, Red.)	2540	2210	2415	2310	2285	2160
FT (°F, Red.)	2640	2385	2520	2395	2385	2185
Ash Viscosity Temperature:						
T_{cv} (°F)	2740	2410	2615	2510	2485	2360
T_{250} (°F)	>2800	2403	2415	2224	2329	2252
Ash Components:						
Dolomite Ratio	52.81	81.12	24.00	48.12	40.64	71.92
Base/Acid Ratio	0.17	0.40	0.39	0.67	0.48	1.03
Ash Type	Lignite	Lignite	Bitum.	Bitum.	Bitum.	Lignite
Slagging/Fouling Indices:						
Fouling Index[a]	Low	Low	Medium	Low	Medium	Low
Fouling Index[b] (RF)	N/A	N/A	0.30	0.20	0.41	0.82
Slagging Potential (RS)	2358[d]	2126[d]	1.1[c]	1.8[c]	1.9[c]	2144[d]
Predicted ST (°F, Red.)						
Gauger[1]	2450	2300	2180	2130	2160	N/A
Schaefer[2]	2400	<2000	2040	<2000	2320	<2000
Bryers and Taylor[3]	2360	1983	2339	2179	2282	2127
Sondreal and Ellman[4]	2781	2297	2268	2100	2158	2216

Slagging/Fouling Indices[5]:

a. Based on Na_2O content in ASTM ash for coals with lignite and bituminous ash.

b. RF = Base/Acid Ratio x Na_2O for eastern coals.

c. RS = Base/Acid Ratio x % S in dry coal for eastern coals.

d. $RS = \frac{(\text{max. HT}) + 4\ (\text{min. IT})}{5}$ for lignitic ashes.

presented and defined in the table. For the lignitic ashes, slagging severity is classed as medium for RS between 2250 and 2450 and classified as high for RS between 2100 to 2250. For the eastern coals, RS between 0.6 and 2.0 is indicative of medium slagging severity.

The predicted ash softening temperatures developed by previous researchers are based on ash composition. The correlations were derived from different coal data bases, but all include bituminous and some lignitic coals of the United States. In general, these correlations imply that with the addition of calcium-based sorbents, the predicted softening temperatures decrease. ASTM measured softening temperatures, also included in Table 5-3, do not necessarily match the predicted values. This may be due to considerable scatter in the data upon which the correlations were based. Low ash softening temperature is an indication that slagging and fouling may cause problems. Softening temperature, often referred to as the ash fusion temperature, is the temperature most often used for boiler design purposes to avoid slagging and fouling.

5.4 Concentration of SO_x Species

The two principal gas phase sulfur species for pulverized coal combustion systems are SO_2 and SO_3, both of which were measured for selected test conditions. SO_2 was routinely measured during sorbent injection tests utilizing the DuPont continuous SO_2 monitor and sampling system described previously. As an independent check of the continuous monitor system, measurements of SO_2 were made utilizing EPA Reference Method 6 for selected test conditions. SO_3 was measured for the same conditions using the sampling method of controlled condensation. Results of these measurements made for full load, staged operation of the RSC DMB firing Utah coal with and without sorbent injection are listed in Table 5-4. The levels of SO_3 measured were all less than one percent of the measured SO_2 concentration, which is typical for SO_3 levels in field operating systems. Because of the accuracy of the method, levels less than 1 ppm are usually considered to be essentially zero. There is good agreement between the two methods used to determine SO_2 concentrations, with the largest relative difference in the measurements of

TABLE 5-4. MEASURED LEVELS OF SO_x SPECIES WITH- AND WITHOUT SORBENT INJECTION

Test No.	21.14	22.3	23.3
Coal	Utah	Utah	Utah
Load (10^6 Btu/hr)	65.1	104.0	101.0
SR_B (% TA)	72	69	70
SR_T (% TA)	119	119	119
Sorbent	---	---	Vicron
Location	---	---	Terts
Ca/S	---	---	2.06
SO_3[1] @ 3% O_2, dry (ppm)	0.16	0.56	0.14
SO_2[2] @ 3% O_2, dry (ppm)	500	578	422
SO_2[3] @ 3% O_2, dry (ppm)	639	620	456

1. SO_3 by Controlled Condensation

2. SO_2 by EPA Reference Method 6

3. SO_2 by Dupont Continuous Analyzer

Test 21.14. The measurement of SO_2 using the manual EPA method represents a single sample and may not be representative of the test conditions. Better agreement was achieved for the other test conditions with duplicate samples.

6.0 SUMMARY OF RILEY STOKER CORPORATION DMB PERFORMANCE

The first phase of testing to evaluate RSC second-generation Low-NO_x burner performance and sulfur capture involved the optimization of a prototype RSC Distributed Mixing Burner. Optimization included the development of a spreader design to achieve acceptable efficiency and flame characteristics. SO_2 reduction potential via injection of calcium-based sorbents through both the coal nozzle passage and tertiary air ports was evaluated with three different fuels. Detailed measurements were made at selected conditions to characterize burner performance.

6.1 Optimization of Combustion Performance

Riley Stoker Corporation DMB performance was observed to be very sensitive to its adjustable burner parameters.

Coal Spreader Design. As in previous tests of RSC equipment at the test facilities located at EER, the design of the coal impeller was a critical parameter in determining flame shape and operating characteristics. The blow back of combustion products through the open spreader support pipe was the principal operational characteristic sensitive to spreader design. Although this blowback effect would not be experienced in practical field application with a closed support pipe, it does indicate a change in pressures and flow patterns produced at the end of the spreader. Spreader design modification was necessary to achieve stable flames with relatively low-volatile Indiana coal. The optimum spreader design utilized a 4-in. support pipe with four equally spaced, short blades set at an angle of 28°.

Coal Nozzle Position.The RSC DMB coal nozzle was designed to vary the primary setback. Retracting the nozzle tended to shorten the length of the flame, but its effect was dependent on spreader design.

Coal Spreader Position. In general, retraction of the coal impeller toward the throat of the nozzle venturi increased the coal head pressure with little effect on flame shape. Again, the actual effect was dependent on spreader design, but in most cases if the coal head pressure became greater than about 10 in. H_2O, blow back of combustion products through the spreader support pipe would result.

Secondary Air Register Vane Position. The range of register positions that produced stable conditions and acceptable flame shape was very narrow. Closing the register vanes to less than 20^o open tended to increase flame length. Opening the registers more than 30^o open resulted in the base of the flame lifting off the burner exit with resulting instability.

Secondary Air Bias. Best performance was obtained when the secondary air flow was equally distributed to the inner and outer passage. Bias to either passage resulted in longer flames.

Tertiary Air Velocity. Increasing the tertiary velocity from 90 ft/sec to about 200 ft/sec with variable air inserts, while maintaining a burner zone stoichiometry of 70 percent, tended to decrease flame length. The additional mixing enhanced by jet entrainment produced corresponding higher NO_x emissions.

Burner performance in the optimized configuration is listed in Table 6-1 for each coal tested.

6.2 SO_2 Reduction Potential

The reduction of SO_2 emissions with the injection of sorbents through burner passages was evaluated for each coal with three sorbent/injection location combinations; Vicron (limestone) through the tertiary air ports, Vicron into the pulverizer with the coal, and hydrated lime through the tertiary air ports. Injection of hydrated lime material through the tertiary

TABLE 6-1. SUMMARY OF RILEY STOKER CORPORATION DMB PERFORMANCE

Coal	Utah	Indiana	Illinois
Flame Length (ft)	20	19-20	19-20
Stability at 60% Capacity	Acceptable at SR_B = 70% TA	Acceptable at SR_B = 90% TA	Acceptable at SR_B = 70% TA
Carbon Utilization (%)	98.9	98.8	99.0
NO_x Emissions Corrected to 3% O_2 (ppm)	210	235	218

ports proved to be most effective in SO_2 reduction, achieving an estimated 50 percent capture at Ca/S = 2.0 for each coal. Injection location did not make a significant difference in SO_2 reduction with the limestone material, with capture in the range of 35 percent at Ca/S = 2.0. There was no measurable effect of coal composition on the degree of SO_2 reduction achieved with any of the sorbent/injection location combinations. The measured SO_2 capture at low load (60×10^6 Btu/hr) was slightly lower for each combination of sorbent and injection location and, as in the case of full-load tests, there was no appreciable effect of injection location on the effectiveness of the Vicron.

6.3 Summary of Riley Stoker DMB Results

The performance of the RSC DMB was verified over typical boiler operating ranges of load and excess air. Combustion efficiency was acceptable for the test furnace and measured NO_x emissions were well below New Source Performance Standards (NSPS) levels for coal fired boilers. In summary, the Riley Stoker DMB burner exhibited:

- Optimized NO_x emissions from the three coals tested ranged from 205 to 245 ppm corrected to 3 percent O_2.
- Carbon utilization exceeded 98.8 percent for all coals at optimum conditions.
- There was no measurable effect of coal composition on the degree of SO_2 reduction with any of the sorbent/injection location combinations.
- Injection of hydrated lime through the tertiary air ports provides the most effective SO_2 capture, achieving an estimated 45 to 57 percent at a Ca/S molar ratio of two.
- Injection location did not make a significant difference in SO_2 reduction with limestone. SO_2 capture was approximately 35 percent at a Ca/S molar ratio of two.

NOMENCLATURE

A_c Weight percent ash in coal.

Ap Weight percent ash in particulate matter.

Ca/S Calcium-to-sulfur molar ratio, based on calcium in sorbent and sulfur in coal.

C_b Carbon burnout, in percent. $C_b = \left[1 - \frac{\left(\frac{Cp}{Ap}\right)}{\left(\frac{C_c}{A_c}\right)}\right] \times 100\%$.

C_c Weight percent carbon in coal.

Cp Weight percent carbon in particulate matter.

DMB Distributed Mixing Burner.

EER Energy and Environmental Research Corporation.

EPA United States Environmental Protection Agency.

FT Fluid temperature of ash.

HT Hemispherical temperature of ash.

IDT Initial deformation temperature of ash.

LIMB Limestone injection with multistage burners.

LOI Weight loss on ignition of sample upon heating, in percent.

LWS U.S. EPA Large Watertube Simulator combustion test facility.

MAF Analysis of coal reported on moisture and ash-free basis.

MMF Analysis of coal reported on moisture and mineral matter-free basis. Mineral matter consists of ash and sulfur in coal.

RSC Riley Stoker Corporation.

SR_B Burner zone stoichiometry, represents percentage of air required for stoichiometric combustion passing through burner exit, including primary and secondary air.

SR_T Overall, or total, stoichiometry represents percentage of air required for stoichiometric combustion passing through primary, secondary, and tertiary passages.

ST Softening temperature of ash.

TA Theoretical air required for stoichiometric combustion.

$v_{injection}$ Sorbent injection velocity, ft/s.

$v_{tertiary}$ Tertiary air velocity, ft/s.

λ Velocity ratio defined as $\frac{v_{tertiary}}{v_{injection}}$.

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APPENDIX A

QUALITY ASSURANCE

A.0

The collection and analysis of quality data is key to the success of this program. Therefore, all necessary steps were taken during the DMB test series to ensure data quality. Specific Quality Assurance (QA) program objectives as outlined in Table A-1. These objectives were based on the program requiremens and the precision and accuracy levels achievable by the selected measurement methods. Table A-2 lists the sampling procedures for each measurement. The procedures are standard EPA, ASTM, or other recognized methods. The following QA procedures utilized during this progrtam are divided into standard (daily routine) and detailed (selected test conditions) measurements:

Standard Measurements

- Air Flow Distribution
- Air Preheat and Combustor Wall Temperatures
- Gas Phase Species--Continuous Monitoring
- Pretest Oil Check
- Particulate Samples (Grab and High Volume)
- Fuel Size Distribution
- Time Limitation for Valid Data

Detailed Measurements

- Instrument Performance Tests
- Manual Methods--SO_3, Particulate
- Sorbent Feed Rate Calibrator

TABLE A-1. PROGRAM OBJECTIVES FOR MEASUREMENT PRECISION, ACCURACY AND COMPLETENESS

Parameters	Measurement Methods	Reference	Precision: Relative Standard Deviation (%)	Accuracy (%)
Burner Settings	Direct Inspection		10	10
Air Distribution	Calibrated Venturi Flowmeter		4	5
Air Flow Rate and Distribution	Thermocouples		5	5
Fuel Flow Rate	Weigh Belt Feeder		4	10
Combustor Wall Temperature	Thermocouples		5	5
NO/NO_x	Continuous Monitor Chemiluminescence	EPA Performance Specification 2	2	20
CO	Continuous Monitor NDIR		2	20
CO_2	Continuous Monitor NDIR	EPA Performance Specification 3	2	20
SO_2	Continuous Monitor UV	EPA Performance Specification 2	2	20
O_2	Continuous Monitor (Paramagnetic)	EPA Performance Specification 3	2	20
SO_3	Controlled Condensation	Process Meas Proc EPA 68-02-2165, 2/77	20	20
Particulate Mass Loading	EPA Method 5		12	20
Solid Composition	Ultimate and Proximate Analyses (ASTM)	ASTM	5	5
Fuel Size Distribution	ASTM Method	ASTM D197	10	10

(continued)

TABLE A-1 (Continued)

Parameters	Measurement Methods	Reference	Precision: Relative Standard Deviation (%)	Accuracy (%)
Flame Characteristics	Color Video and Direct Inspection		Qualitative	Qualitative
Sorbent Feed Rate	Volumetric Feeder		10	10
Windbox Pressure	Magnahelic-Bourdon tube		10	10

TABLE A-2. SAMPLING PROCEDURES

Parameters	Measurement Methods	Sampling Location Selection Criteria	Sampling Procedure	Sampling Frequency	Reference
Burner Settings	Direct Inspection	Burners	Direct Inspection	Every Test Condition	
Air Flow Rate and Distribution	Calibrated Venturi Flow-meter	Air Inlet Ducts		Every Test Condition	
Air Preheat Temperature	Thermocouples	Burner		Every Test Condition	
Fuel Flow Rate	Weigh Belt Feeder	Upstream of Pulverizer	Continuous Direct Weight	Every Test Condition	
Combustor Wall Temperature	Thermocouples	Selected Locations in Furnace		Every Test Condition	
NO/NO_x	Continuous Monitor Chemiluminescence	Modified EPA Performance Specifications for Continuous Monitors	Extractive (See Text)	Continuous	Fed Register Vol 44 No 197 Oct 10, 1979 pp 58602-58636
CO	Continuous Monitor NDIR				
CO_2	Continuous Monitor NDIR				
SO_2	Continuous Monitor UV				
O_2	Continuous Monitor (Paramagnetic)				
SO_3	Controlled Condensation	EPA Process Measurement Procedures		Selected Conditions	
Particulate Mass Loading	EPA Method 5	EPA Level 1 Solid Sampling Procedures	Extractive	Selected Conditions	Fed Register Vol 42 No 160 Aug 18, 1977 pp 41776-41782
Solid Composition	Ultimate and Proximate Analyses (ASTM)		Grab Sample/ High-Volume Baghouse	Daily	EPA 600/7-78-201 p 105
Fuel Size Distribution	ASTM Method	ASTM D197	Multipoint Grab Sample	Daily	ASTM D197
Flame Characteristics	Color Video and Direct Inspection	Furnace Sample Ports		Every Test Condition	
Sorbent Feed Rate	Volumetric Feeder			Every Test Condition	
Windbox Pressure	Magnahelic - Bourdon Tube			Every Test Condition	

The incorporation of the QA procedures into the test plan, ensured the collection of quality data resulting in more accurate results and conclusions. The following selections discuss these procedures.

A.1 Standard Measurements

A.1.1 Air Distribution

The distribution of combustion air between the burner passages was determined through direct measurement of the air flow rate to each passage using 18-inch venturi flowmeters. Each venturi was calibrated using a standard pitot tube immediately prior to these tests. During the tests, the pressure drop of the air through each venturi was continuously monitored using low pressure electronic pressure transducers. Each transducer was calibrated manually prior to testing each day at pressure differentials of 0 in. and approximately 3-in. H_2O static pressure. Periodic transducer calibrations were also conducted throughout the test day as required.

A.1.2 Air Preheat and Combustor Wall Temperatures

Type K (Chromel/Alumel) thermocouples were used to monitor the combustion air and furnace wall temperatures, ASTM Standard E230-77 specifies that the standard limit of error for Type K commercial thermocouples be $\pm$ 2°C or $\pm$ 0.75 percent between 0° and 1250°C. To assure that the thermocouples were functioning during testing, a continuous output of the temperatures is printed on the computer data acquisition printout. In case of thermocouple malfunction, the damaged TC was immediately replaced if possible. If, due to location restrictions, it was not practical to replace the TC while testing, it was replaced prior to the next day of testing.

A.1.3 Gas Phase Species

The exhaust gas phase species composition was measured using the LWS laboratory sampling system as outlined in Figure A1. Flue gas was sampled immediately upstream of the LWS system SO_x and particulate scrubber ensuring

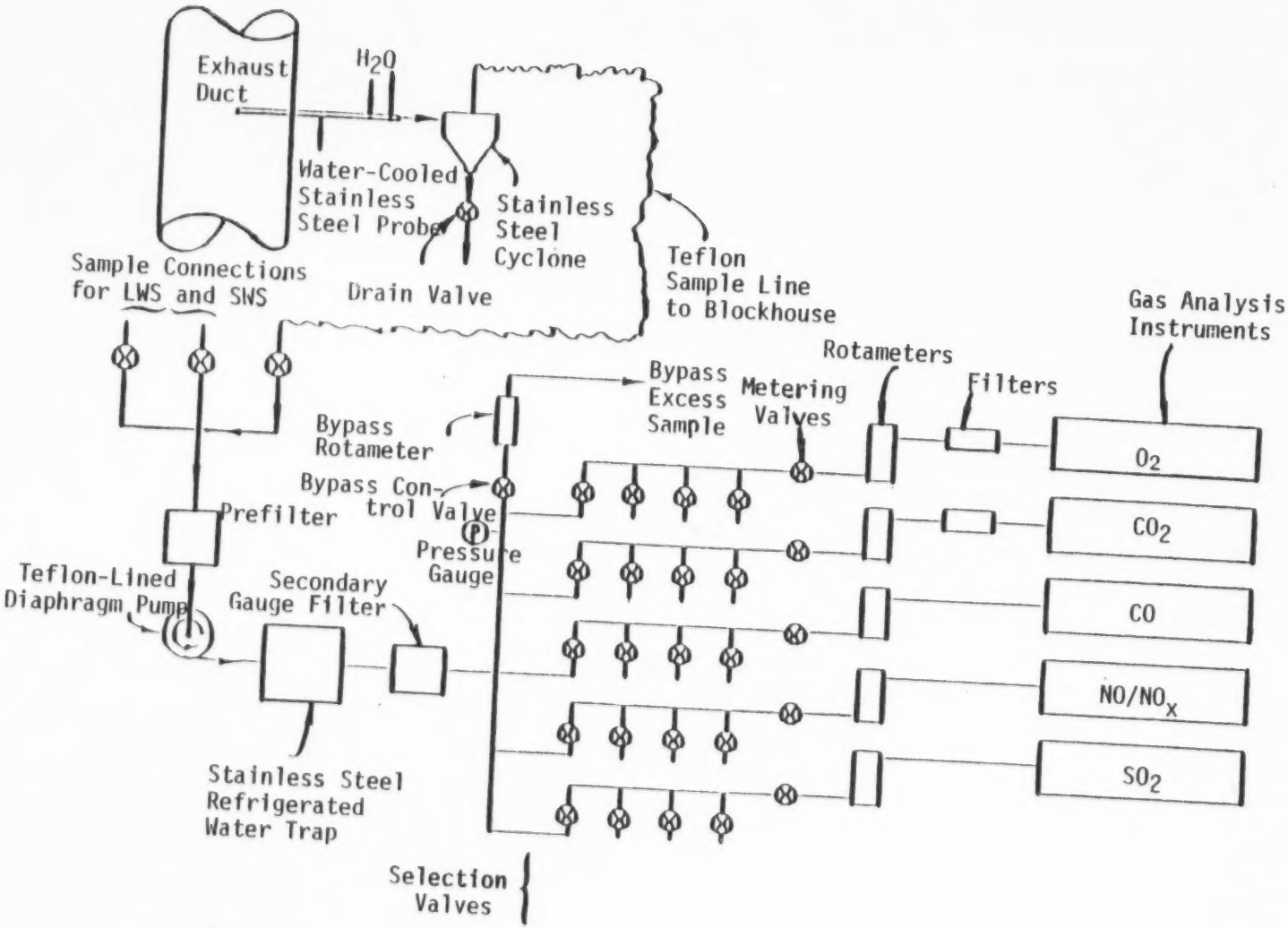

Figure A-1. The Large Watertube Simulator furnace (LWS) sample train.

that the flue gas sample was representative of the furnace effluent. A single sample probe which draws from the center of the duct was used. All materials in contact with the sample gas are limited to glass, stainless steel, Teflon, and a small amount of Kel-F (valve seals) since these materials have been demonstrated as essentially nonreactive to the gases measured over the temperature range involved in this system.

This system is generally satisfactory for most tests, but may result in SO_2 loss under conditions where SO_2 sorbents such as limestone are present. Therefore, an independent SO_2 sample system was utilized. The system included a phase discrimination probe and a heated sample line, filter, and pump to prevent condensation before the gas sample entered the analyzer. The temperatures were monitored throughout the entire SO_2 sample system to ensure that the sample remained heated to proper temperatures (200°F). Table A-3 shows an example of the daily test log of temperatures. The filter may introduce an error in SO_2 concentration measured during sorbent injection due to agglomeration of particles on the filter, thus creating a potential scrubbing effect independent of the injection parameters. Therefore, this filter was changed at least after every two tests of sorbent injection had been completed or as necessary to maintain a clean filter.

Table A-4 lists the continuous gas analyzers used during these tests. To ensure accuracy, the instruments are operated according to EPA Performance Standards 2 and 3. Each instrument was calibrated with three certified gases; a zero gas and two span gases, at approximately 50 and 90 percent of scale. To increase accuracy and precision, the instruments were calibrated approximately every two hours during the test day.

A.1.4 Pretest Oil Check

A pretest oil check was completed daily, prior to switching the system to coal. The oil check is used to warm up the system and as a QA check on the overall LWS process system. The oil check is a ratio between the calculated and measured load. The calculated load is a theoretical determination based on the heating value of the fuel oil and the oil flow rate. It

TABLE A-3. SO_2 SAMPLE SYSTEM DAILY LOG FOR 7/26/83 (^oF)

Time	Exiting Probe	Hot Box	Pump Inlet	Analyzer In	Pump Head
1130	287	400	270	200	177
1200	239	400	279	200	200
1230[1]	154	400	279	205	201
1300	300	400	276	200	200
1330	312	400	279	204	207
1400	260	400	280	204	205
1430	310	400	280	205	204
1500[2]	280	320	270	204	206
1530	300	300	257	209	205
1600	280	300	248	210	204
1630	260	300	246	210	210
1700	286	300	243	211	196

[1] Probe plugged.

[2] Reduced hot box temperature. Filters were burning.

TABLE A-4. CONTINUOUS GAS ANALYZERS

Gas Measured	Type of Instrument	Manufacturer	Model No.	Range
NO, NO_x	Chemiluminescent	Thermo Electron Corp (TECO)	10 AR	1000 ppm
CO	Nondispersive Infrared (NDIR)	Anarad, Inc.	AR500R	500 ppm/2500 ppm
CO_2	Nondispersive Infrared (NDIR)	Anarad, Inc.	AR500R	25 percent
O_2	Paramagnetic	Taylor Servomex	Type OA 272	10/25 percent
SO_2	UV Absorption	DuPont	400	5000 ppm

is independent of the air flow system. The measured load is a function of the O_2 concentration measured in the exhaust, and the air and fuel flow rates. The resultant ratio indicates the overall acuracy of the measurement system-transducers continually monitoring instruments, temperatures, and fuel flow rate. The difference between the calculated and measured load must be less than 10 percent in order to proceed with testing; however, during the DMB test series, the oil check was generally 5 percent or less, ensuring overall system accuracy.

A.1.5 Particulate Samples (Grab Sample)

Analysis of the fly ash is essential in determining the burner/furnace performance. Therefore, during all of the major test conditions during this test series, fly ash samples were collected to obtain representative samples. Two methods were utilized:

1. Grab Sample
2. High-Volume Bag House Filter

The grab sample was collected using a standard sampling system with an ejector and a small cyclone with the sample probe in the center of the exhaust duct. The high-volume bag house draws a representative sample into the bag house using an exhauster and with the particulate matter collected on the bags. Air pulses through the filter every 15 seconds causing the particulate to drop into the collection cointainer. Prior to every test condition, the bag house was purged to ensure that the subsequent sample collected was representative of that specific test condition. Using percent carbon in the ash as a relative indicator of accuracy between the high volume sampler and grab sample resulted in an average relative accuracy of 9.3 percent. Since this is less than 10 percent, for most of the detailed analysis, the high-volume sample was used. This was due mainly to the large volume of sample which could be obtained during a short period of time in comparison to the grab sample.

A.1.6 Fuel Size Distribution

The coal fineness affects the combustion performance of the burner; therefore, it was necessary to determine the coal fineness daily. The coal sample was drawn using an ASME-designed coal sample (ASME PTC 32) at a sample point location downstream of the pulverizer. The main concern for the burner performance was to ensure that the coal size distribution resulted in at least 70 percent passing through 200 mesh (75 m). During normal testing, if the fineness was not satisfactory, the mill classifiers were reset prior to the next test day.

The sieves were standard ASTM sieves. These sieves were calibrated using the National Bureau of Standards Standard Reference Material (SRM) 1004. SRM 1004 is a set of calibrated glass beads, with specific cumulative size distribution determined by microscopic measurement. Table A-5 summarizes the results. The relative accuracy of the calibrations is 3.7 percent for the roto-tap and 9.3 percent for manual tapping, which are within program limits. Generally, during testing the manual method for coal size distribution is used.

A.1.7 Valid Data Acquisition

The outputs of all continuous instrumentation (flow rates, temperatures, and emissions) are converted to electrical signals, put into digital notation, and supplied to a Hewlett Packard computer. The computer processes this data and provides a real-time indication of input and output parameters. As a QA procedure, during a given test condition, valid data points are recorded which summarize that test. The valid data points yield average inputs and outputs, by manually inputting the gaseous concentrations. In addition, temperatures and flow rates are corrected if required to ensure that the results of the specific test includes only valid data and conditions.

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TABLE A-5. SUMMARY OF ASTM SIEVE CALIBRATION

Sieve No.	Sieve Effective Opening (Microns)	Weight % Finer (EER Sieves)	Weight % Finer NBS-SRM	Relative Accuracy (%)
200[1]	77	49.1	51.0	3.73
200[2]	77	55.69	51.0	9.20
200[2]	77	55.84	51.0	9.49

[1] Using Roto-Tap

[2] Manual Tap

A.1.8 Fuel Flow Rate

The fuel input feed rate is determined using a direct weigh method. The conveyor belt which feeds coal to the pulverizer is equipped with a load cell which measures the difference in the belt weight between the supply and return sides. The load cell has an accuracy of $\pm$ 0.1 percent. However, it is necessary to calibrate the load cell dynamically and adjust the electronic set points according to the manufacturer's specification. The feeder was calibrated prior to the test series and during the tests when conditions required (i.e. replace belt or roller). Therefore, an accurate, continuous fuel input indication is determined.

A.2 Detailed Measurements

During certain test conditions, selected detailed measurements were conducted in accordance with the QA and Program Test Plans. These measurements and QA procedures are discussed in the following subsections.

A.2.1 Instrument Performance Test

The LWS continuous monitoring system is operated according to EPA Specifications 2 and 3. Part of these specifications include instrument performance test guidelines. As part of the QA plan for this test series, an abbreviated instrument performance test was conducted--relative accuracy and 2-hour drift. Table A-6 summarizes these results.

The relative accuracy was determined by comparing the instrument values to values obtained using EPA Reference Methods. There is currently no performance specification fo the CO monitor or standard reference method for CO determination. Therefore, relative accuracy for CO could not be determined, but the 2-hour drift test was conducted in accordance with the guidelines for the other analyzers. The results show that for both relative accuracy and 2-hour drift tests, the O_2 and NO_x instruments were within specifications outlined by EPA. The relative accuracy of the DuPont SO_2 instrument was not within EPA specifications. The result is biased by a large error, almost

TABLE A-6. INSTRUMENT PERFORMANCE TESTS SUMMARY

Instrument/Manufacturer	Relative Accuracy (%)	EPA Specification	2-Hour Drift Test			
			Zero	EPA Specification	Calibration	EPA Specification
O_2 - Taylor Servomex	7.32	$\leq$ 20	0.26	$\leq$ 2.0	0.11	$\leq$ 0.4
CO_2 - Anarad, Inc.	3.91	$\leq$ 20	0.11	$\leq$ 2.0	0.21	$\leq$ 0.4
SO_2 - DuPont	24.46	$\leq$ 20	0.79	$\leq$ 2.0	0.77	$\leq$ 2.0
NO, NO_x - TECO	6.43	$\leq$ 20	0.43	$\leq$ 2.0	1.28	$\leq$ 2.0
CO - Anarad, Inc.	---	---	0.60	---	4.76	---

Note: O_2 & CO_2 - EPA Method 3 (Orsat)
SO_2 - EPA Method 6
NO_x - EPA Method 7

28 percent, in one of the five Method 6 samples. The other four samples were in better agreement with the SO_2 concentration simultaneously measured by the DuPont analyzer. Excluding the sample with the large error improves the relative accuracy to 16.2 percent, which is within EPA Performance Specification 2. The CO calibration drift was higher than that allowed for the other monitors. This may be related to the high sensitivity of the instrument at the high span valves. However, maintaining frequent calibrations during testing minimized the error.

A.2.2 Sorbent Feed Rate Calibration

To determine sorbent effects on SO_2 capture, it is necessary to accurately determine the sorbent feed rate. The sorbent feed rate was calibrated dynamically prior to the sorbent injection tests. During each sorbent injection test, feed rate was simultaneously calculated using the bag count of sorbent used vs time elapsed. This feed rate was compared to the calibration curve to ensure accurate sorbent feed rates.

Metric Conversion Factors

1 kg = 2.2046 lb

$K = (°F + 459.67)/1.8$

1 m = 39.370 in.
= 3.2808 ft

1 m^2 = 10.764 ft^2

1 W = 3.4123 Btu/hr